THE UNIVERSITY OF ALBERTA

THE FRACTURE OF PVC LINE PIPE

BY

© ALEXANDER CREVOLIN

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Fracture of PVC Line Pipe" submitted by Alexander Crevolin in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

Long running fractures have occurred in both steel and plastic gas transmission line pipe. Occasionally sine wave fracture patterns have developed, but the reason for this occurence is not well understood. Knowledge of a sine wave fracture in 1-1/4 inch polyvinylchloride pipe prompted the study of fracture in this particular pipe material.

An attempt was made to apply linear elastic fracture mechanics to plastic pipe with the aim of determining the minimum fracture toughness. Crack velocities were measured and a linear relationship between fracture toughness and crack velocity was demonstrated. It was also found that the occurence of long running fractures depended upon the radial constraints imposed upon the pipe wall, such as that arising from burial in soil. These radial constraints on the pipe wall promoted long running fractures and occasional sine wave fracture patterns. Crack velocity measurements indicated no abrupt change in fracture velocity with the development of a sine wave fracture.

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LIST OF SYMBOLS

a	- one half the crack length
r_y	- plastic zone size
s	- speed of sound at the exit of a duct
s_o	- speed of sound for initial conditions
u	- flow velocity at the exit of a duct
v	- crack propagation velocity
B	- material wall thickness
C_1	- longitudinal stress wave velocity
C_2	- transverse (shear) wave velocity
C_3	- Rayleigh wave velocity
D	- pipe diameter
E	- Modulus of Elasticity
G	- shear modulus
$\mathcal{G}$	- strain energy release rate
$\mathcal{G}_c$	- strain energy release rate at the onset of rapid fracture propagation
K	- stress intensity factor
K_I	- stress intensity factor for mode I fracture
K_c	- stress intensity factor for the onset of rapid fracture propagation

P	- effective line pressure
P_c	- critical pressure for crack propagation
P_o	- initial line pressure
PVC	- polyvinyl chloride
α	- parameter relating C_3 and C_2
β	- plastic zone parameter
γ	- ratio of specific heats of a gas
ε	- strains
ρ	- density mass/unit volume
σ_c	- stress at the onset of rapid fracture propagation
σ_x	- stress in the x direction
σ_y	- stress in the y direction
σ_Y	- yield stress
ν	- Poisson's ratio

CHAPTER I

INTRODUCTION

1.1 Introduction

The everpresent demand for efficiency and economy in design requires a thorough understanding of the service behavior and failure of engineering materials. As the demand on engineering materials becomes more stringent the classical approach to design based on strength of materials with emphasis on yield strength or maximum allowable strain has proven to be inadequate. The successful application of computers to the design function requires an ability to provide accurate data. In the space age, this data encompasses more than a mere statement of yield strength and factor of safety. Industry can no longer afford to condone the extravagance of over design and "ignorance factors".

The inadequacy of these early approaches has been recognized since the days of Leonardo da Vinci. He had observed that short steel wires in tension were stronger than long wires of the same material and thickness. Today, da Vinci's observation is explained by the greater probability of a flaw occurring in a long wire. Griffith (1) in 1921 had considered the weakening effect of a flaw in an infinite plate. His rupture criterion provided a means of evaluating the maximum permissible flaw size for a given stress level. A number of

other researchers had considered flaw effects and crack propagation, but the subject remained largely an area of academic interest until the nineteen forties.

The frequent failures in Liberty Ships during World War II shook the foundation of the engineering world. Failures were occurring well below maximum design stresses. Similar unexpected failures occurred in oil storage tanks, the de Haviland Comet aircraft and gas transmission pipe lines. In an attempt to explain these failures, Irwin and Orowan considered Griffith's rupture criterion. An acceptable explanation to the De Haviland Comet failures was proposed. The size of the window opening was found to be very close to the critical crack length for crack extension at the existing stress level. The significance of Griffith's observation that flaws were critical in determining material strength became more fully appreciated.

The introduction of high strength steels and the greater cost of failures in terms of dollars and lives increased the demand for knowledge of fracture. Thus, the concept of fracture mechanics developed in which materials were evaluated by their resistance to crack propagation. A material's capacity to tolerate localized strain without fracture is a material property called fracture toughness. For most materials, toughness is observed to vary with fracture mode, temperature and strain rate. The shear fracture mode is a high energy fracture while the cleavage fracture mode is a low energy fracture. Therefore, the toughness associated with a shear fracture will be greater than that associated with a cleavage

fracture. It is for this reason that the opening or cleavage mode is so important in design consideration. Generally, low temperatures and high strain rates promote a decrease in fracture toughness. Under some conditions, a failure will be an unusually low energy fracture. This type of fracture, which usually exhibits less than expected ductility is termed a brittle fracture. Since this is the lowest energy fracture which could occur, the application of the fracture toughness concept to design demands that the toughness associated with brittle fracture be known. A knowledge of fracture toughness and the associated stress level permits the determination of the maximum flaw size.

1.2 Problem Statement

In this study the brittle fracture of small diameter polyvinylchloride pipe is considered. A service failure (figure 1) was obtained in which a brittle fracture propagated well over 100 feet during the preservice test. A unique feature of the fracture is that the crack propagated in a regular sinewave pattern. It was observed that the pipe had a set curvature as a result of being coiled into rolls. The crack propagated on the side which would be in compression when the pipe was straightened and buried.

The objectives of this study are to;

1. evaluate the toughness of polyvinychloride pipe
2. produce long running fractures under laboratory conditions
3. measure crack velocities

Figure 1 Service Failure

4. show the relationship between crack velocity and fracture toughness
5. observe any peculiar velocity or toughness characteristics of sinewave fracture
6. produce a method of toughness testing of plastic pipe which could be used in industry
7. reproduce and explain sinusoidal fractures.

CHAPTER II

THEORY

2.1 Basic Concepts

Since 1856 when steel first became available in sufficient quantities for structural use, brittle fractures have frequently been observed (2,3). However, it is only in the last twenty years that any progress has been made in the study of brittle fracture.

In 1921, Griffith (1) proposed a new criterion of rupture even though his original object was to study the effect of surface finish on the strength of metallic machine parts subjected to cyclic stresses. He postulated that the maximum tensile strength and maximum extension criterions of fracture were inadequate and that fracture could be better understood by using energy considerations. He stated that if the total energy of the system was decreased with the extension of a crack, there would exist a driving force sufficient to cause crack propagation. He assumed that the energy balance existed between the strain energy released ($\sigma^2\pi a^2/E$) and the fracture surface energy required to create the new surface ($4a\gamma$). a is the half crack length and γ is the surface tension. The criterion can be expressed as,

$$\frac{d}{da}\left(-\frac{\sigma^2\pi a^2}{E} + 4a\gamma\right) = 0 \qquad (1)$$

This leads to the Griffith relation,

$$\sigma^2 = \frac{2\gamma E}{\pi a} \tag{2a}$$

The energy release rate, $\mathcal{G}$, and the surface tension are related such that,

$$\sigma^2 = \frac{\mathcal{G} E}{\pi a} \tag{2b}$$

Irwin (5) and Orowan (6) independently modified the Griffith equation by adding a plastic work term to the surface energy term. In most materials, fracture is accompanied by a certain amount of plastic flow near the crack front. The energy absorbed by this plastic flow is considerably greater than the energy requirements for the creation of new surfaces (in the order of x 10^3 in mild steel) (6). Orowan's expression for brittle fracture of ductile steels was

$$\sigma^2 = \frac{2pE}{\pi a} \tag{2c}$$

where p was the plastic work term. However, since the plastic work of fracture is a little-understood process, any attempt to include a plastic work term for anything but brittle materials leads to difficulties.

A mathematical model based on linear elasticity and a stress

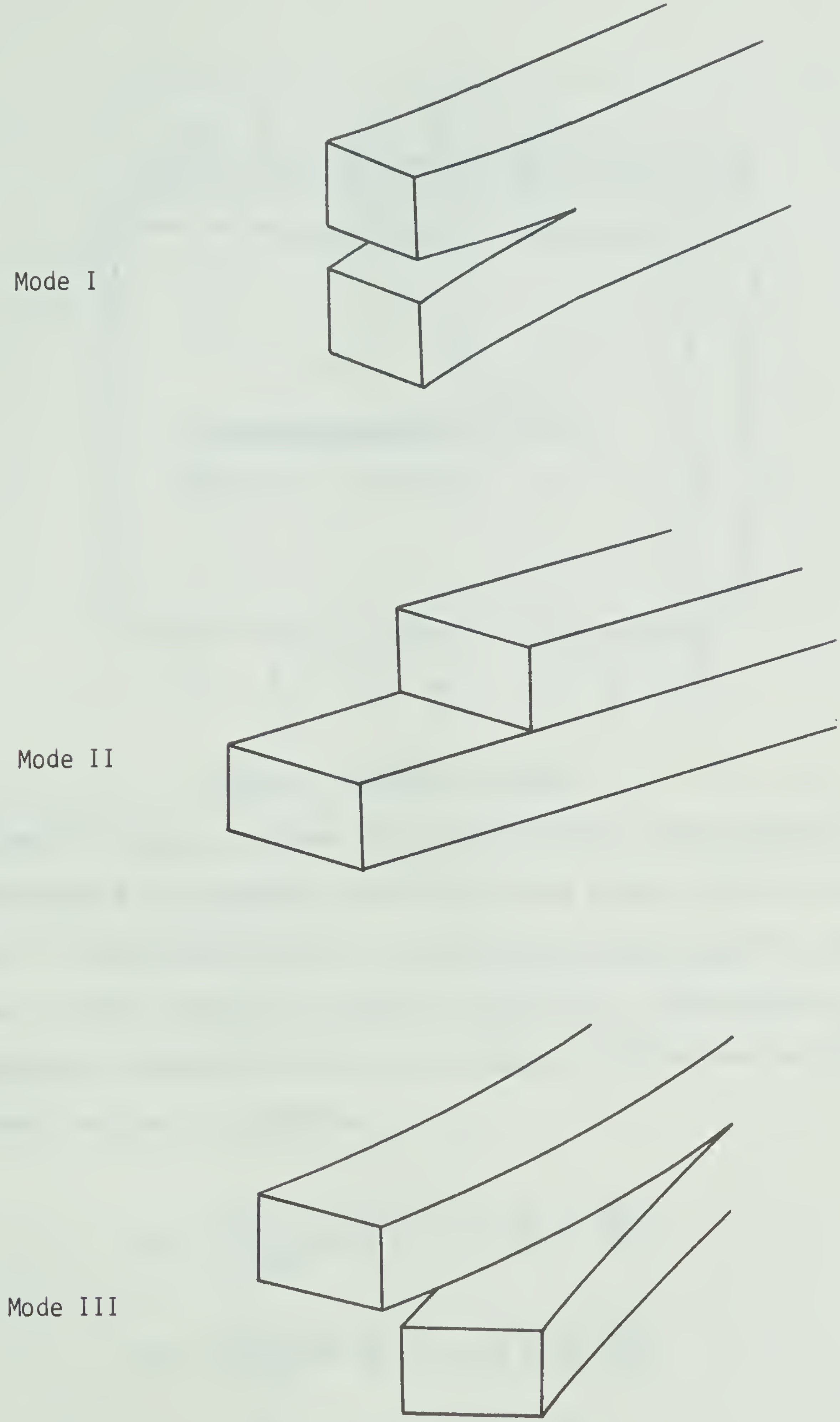


Figure 2 Modes of Fracture

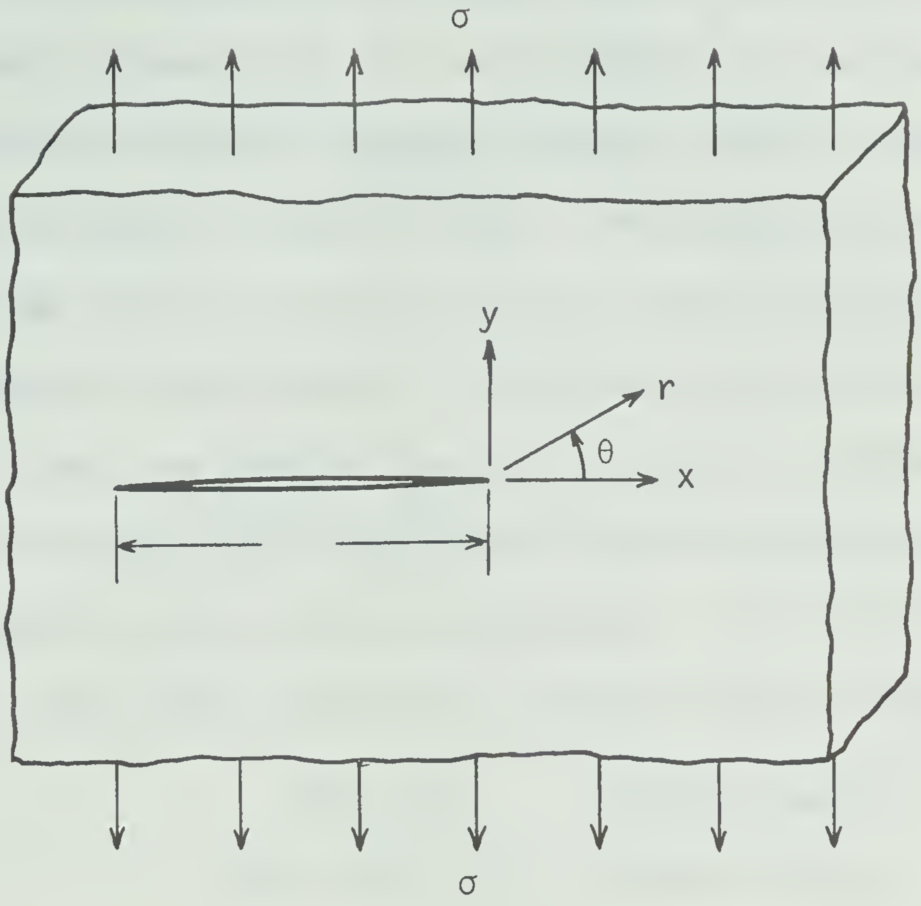


Figure 3 Griffith's Model

intensity factor, K, became very popular in the late nineteen fifties. Westergaard (7) presented a two-dimensional stress solution for a mode I crack (see figure 2) in an infinite plate (figure 3). For a mode I crack, the stress intensity factor is K_I. Westergaard's solution, obtained with the use of complex variables and an Airy stress function, is given as,

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \tag{3a}$$

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \tag{3b}$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2} \tag{3c}$$

The advantage of the linear elastic approach is that the strain energy release rate, $\mathcal{G}$, with respect to crack area provides a description of material toughness without specific reference to the amount of plastic flow occurring. The mathematical model is good provided the gross fracture stress is small compared to the yield strength of the material. If the net section stress approaches the yield stress the plastic zone at the crack tip becomes large compared to the crack length, the elastic field disappears and the stress intensity factor looses significance. For fully linear elastic behaviour, K has been shown to be related to $\mathcal{G}$ as follows,

$$\mathcal{G} E = K^2 \qquad \text{(plane stress)} \qquad (4a)$$

$$\mathcal{G} E = K^2(1-\nu^2) \qquad \text{(plane strain)} \qquad (4b)$$

Stress intensity factors and strain energy release rates with a subscript c indicates critical toughness values or toughness at onset of rapid crack propagation.

Irwin (8) made use of Westergaard's solution to estimate the size of the plastic zone that precedes any crack front. He estimated,

$$r_y = \frac{1}{2\pi} \left(\frac{K_I}{\sigma_Y}\right)^2 \qquad (5)$$

where σ_Y is the yield stress. He considered the plastic zone to be located beyond the physical crack tip and that the effective crack tip was located at the centre of the yielded zone as shown in figure 4a. McClintock and Irwin (9), using Westergaard's solution and

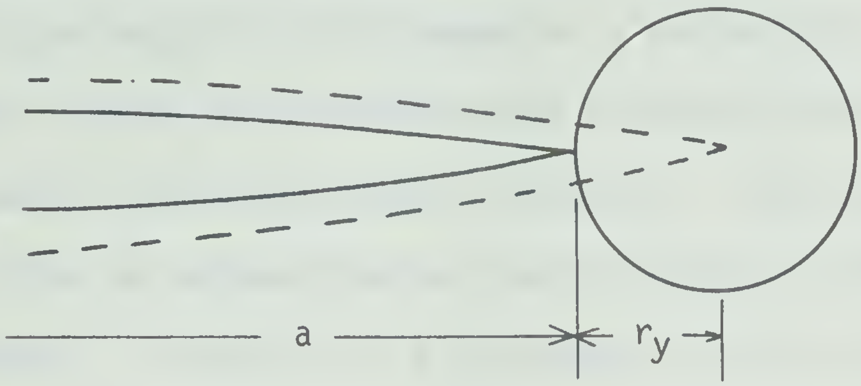


Figure 4a Plastic Zone Irwin (8)

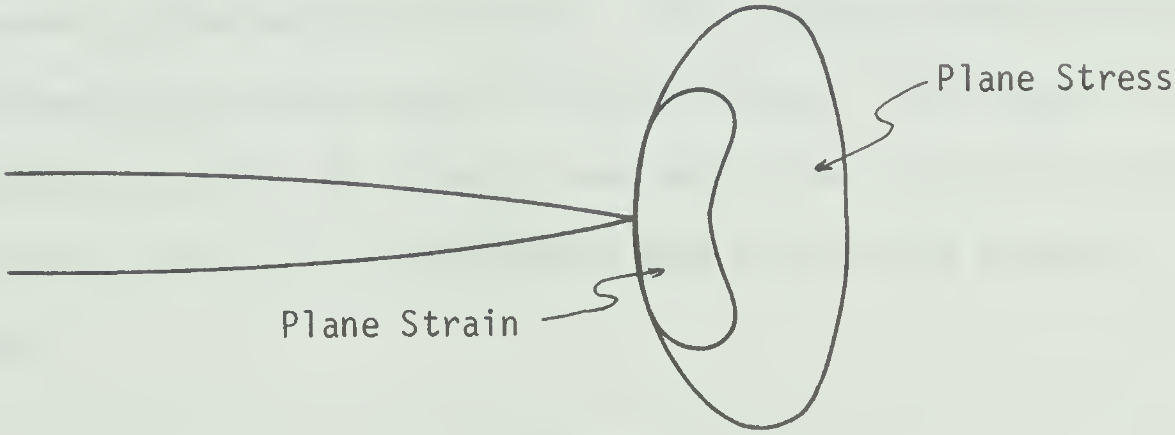


Figure 4b Plastic Zone McClintock and Irwin (9)

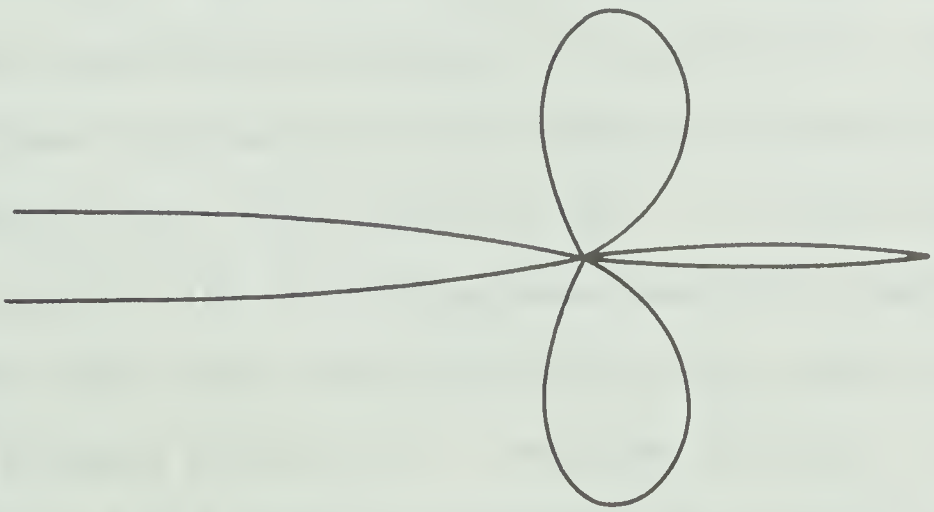


Figure 4c Plastic Zone Wells and Post (10)

Von Mises criterion, estimated the plastic zone shape of figure 4b. Wells and Post (10) illustrated by a photoelastic technique the dynamic stress distribution about a running crack. It suggests a plastic zone shape shown in figure 4c. This plastic zone shape may offer an explanation for the occurrence of tunneling in some fractures. Tunneling in a phenomenon in which a highly irregular crack front spreads ahead of the crack tip.

Regardless of the exact shape of the plastic zone preceding the crack front, the size of the plastic zone is significant in determining the mode of fracture. Irwin's approximation has been used extensively in the study of crack behaviour. An attempt has been made to describe the plastic zone about the crack tip by considering the ratio (β) of the plastic zone size to the material thickness

$$\beta_c = \frac{1}{B} \left(\frac{K_c}{\sigma_Y}\right)^2 \qquad (6)$$

A decrease in the value of β_c indicates a greater degree of plain strain condition or constraint at the crack tip. High constraint at the crack tip promotes brittle behaviour because the resistance to plastic flow in plane strain is high. In steel a value of π seems to coincide with the fracture mode transition (the midway point between plane stress and plane strain or the midway point between shear and cleavage fracture) (11). When the ratio $B/r_y \geq 5\pi$ and $a/r_y \geq 5\pi$, there is a high degree of constraint at the crack tip and valid minimum

toughness values can be obtained (11).

2.2 Crack Velocity Considerations

The maximum velocity of crack propagation in elastic solids is governed by the stress wave velocities associated with each material. Longitudinal stress waves involve dilatation and their velocity is given as

$$C_1 = \left[\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}\right]^{1/2} \tag{7}$$

Shear waves are identified by a transverse or shearing wave motion and travel at a velocity

$$C_2 = \left[\frac{G}{\rho}\right]^{1/2} \tag{8}$$

It can be observed that longitudinal and transverse wave velocities are related by the material properties of the medium.

A third type, Rayleigh waves, propagate over the surface of a body in a fashion similar to ripples on a pond and differ from longitudinal and transverse waves in that they are two dimensional. Timoshenko and Goodier (12) give the Rayleigh velocity of an elastic medium as

$$C_3 = \alpha \sqrt{\frac{G}{\rho}} \text{ or } C_3 = \alpha C_2 \tag{9}$$

where α is determined from

$$\alpha^6 - 8\alpha^4 + 8(3 - \frac{1-2\nu}{1-\nu})\,\alpha^2 - 16[1 - \frac{1-2\nu}{2(1-\nu)}] = 0 \qquad (10)$$

For $\nu = 0$, $\alpha = 0.874$; for $\nu = 0.25$, $\alpha = 0.9194$; for $\nu = 0.50$, $\alpha = 0.9553$. The Rayleigh wave velocity is of particular interest in crack propagation studies because this velocity provides a theoretical upper bound on crack velocities. Most investigators have observed that the maximum obtainable crack velocities are somewhat less than the Rayleigh wave velocity - usually in the order of 0.3 to 0.62 C_2 (13). It has been shown, however, that under certain conditions, velocities in excess of C_3 can be obtained (14).

The velocity of a propagating crack is governed by the available driving force. When the strain energy release rate $\mathcal{G}$, equals the work done in the fracture process, the crack will propagate at a constant velocity. If the strain energy release rate exceeds the energy required for fracture, there exists a driving force which will accelerate the crack. Most materials exhibit an apparent increase of fracture toughness with an increase in crack velocity. As the crack velocity approaches its maximum value, the fracture surface usually becomes very rough. This roughening of the fracture surface, sometimes referred to as hackle, produces greater fracture surface area for a given crack extension. If the strain energy released cannot be dissipated by a single fracture, there will be a tendency for the crack to branch into two or more cracks. The whole

process of fracture is complicated by the fact that the work done at the fracture front may be a function of temperature, strain rate, loading history and a number of other effects.

Irwin (13) has considered the dynamic effects of crack propagation. Irwin postulates that the driving force of a crack must increase with crack speed due to the increased inertia effect of the material in the area of the crack. Also, at high strain rates, each particle near the crack surface behind the crack front is carried past its equilibrium position. This effect has a tendency to superimpose a compressive stress on the tensile stress field about the crack. Irwin concluded that as long as the crack velocity is less than one half the shear wave velocity, these two effects counteract one another. This suggests that the crack extension force is independent of the crack velocity below 0.5 C_2.

Velocity effects in plastics have been studied by Cotterell (15). A relationship between crack velocity and fracture toughness was observed. Cotterell also found that as a crack approached its limiting velocity, the fracture surface became rougher. Cotterell's observations appear to conflict Irwin's analysis (13), but the discrepancy may be attributed to the fact that Irwin did not consider a change in fracture surface with fracture speed. The increased surface roughness results in a larger fracture surface area per unit crack extension which may partially account for the apparent increase in fracture toughness. Chevron markings, commonly observed in mild steel fractures, are a form of surface roughness.

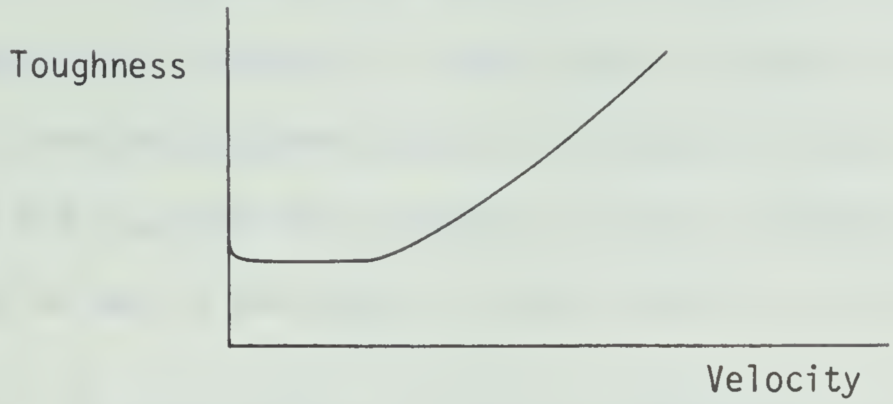


Figure 5a Mild Steel, After Kraft and Sullivan (16)

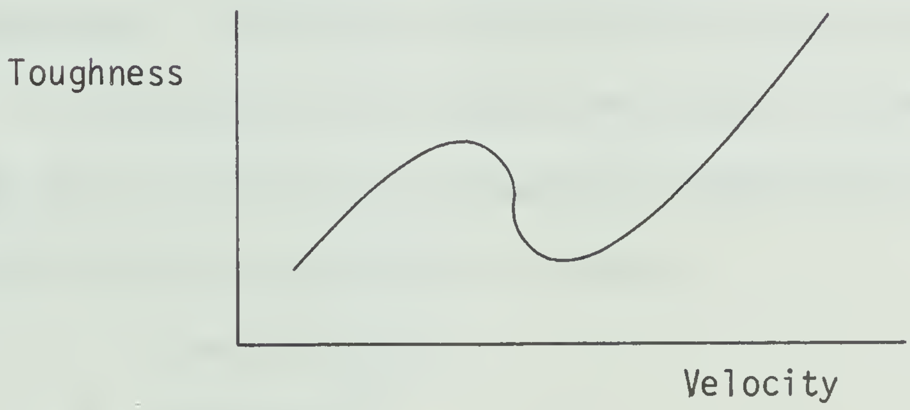


Figure 5b Plexiglass, After Williams et al (17)

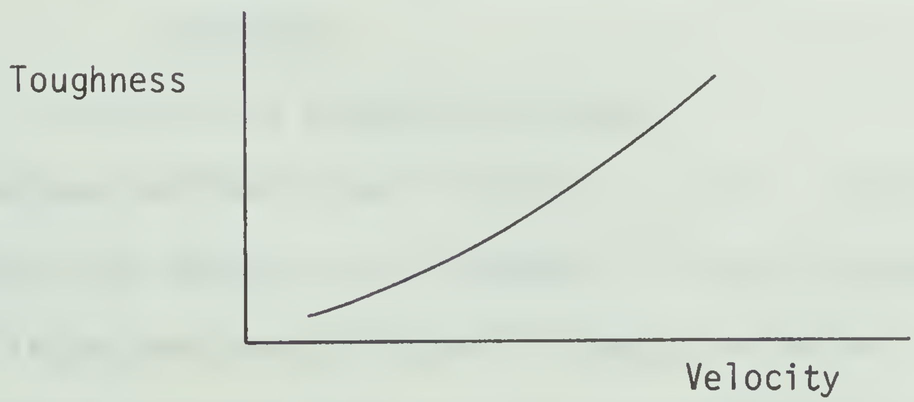


Figure 5c Plexiglass, After Cotterell (15)

Schematic illustration of toughness versus crack velocity are shown in figure 5. They suggest a general trend for an increase of fracture toughness with an increase in crack velocity. Figures 5b and 5c, both for plexiglass, appear different but the difference may be due to the range of crack velocities considered in figure 5b.

5.3 The Application of Fracture Mechanics to Line Pipe

The most extensive studies of line pipe fracture have been conducted by the Battelle Memorial Institute (18,19,20). Their test program is conducted at two sites where service conditions are closely reproduced. The Athens test facility consists of a 673 foot length of 30 inch steel pipe of which the centre 150 feet is the test section. The pipe is artificially flawed and pressurized with natural gas. The following measurements are made:

1. Fracture speed
2. Temperature
3. Pressure decay
4. High speed motion pictures of fracture
5. Accelerometer measurements of pipe expansion following fracture
6. Strain gauge measurements

The West Jefferson test facility is not as large with only a 15 to 20 foot test section. The specimen is filled from 90 to 94 percent with a liquid and pressurized with gaseous nitrogen. Fracture speed, failure pressure and temperature recordings are made. The data obtained from these tests is being used to relate the two thirds size

Charpy V-notch test data and the Battelle Drop Weight Tear test data to these simulated service failures.

The Battelle study has concluded (18):

1. the effect of backfill is of no significance (contrary to our results),
2. the fracture speed is independent of applied stress,
3. a large number of sine wave fractures may propagate simultaneously in a piece of pipe,
4. a shear fracture arrest is typified by a change from an axial path to a helical path.

The fracture of line pipe used for gaseous mediums has the unique property that the length of a single fracture may extend for thousands of feet. This occurs because of the ability of a rapidly propagating fracture to outrun the decompression wave of the gas. The velocity of sound in natural gas is about 1300 feet per second. If the crack should attain a velocity in excess of 1300 feet per second, the stress conditions at the crack front will remain maximum and arrest due to pressure loss is unlikely until the crack velocity decreases. Even if the crack velocity is less than the sonic velocity of the gas, a considerable stress field may exist at the crack front.

Eiber (18) considered a pipe line to be a long open duct of constant cross section. Let u be the flow velocity at the exit of the duct relative to the duct and a be the speed of sound at the exit of the duct. The values u and a can be nondimensionalized by letting

$U = u/a_0$ and $A = a/a_0$ where a_0 is the speed of sound of some reference state. For isentropic flow in a long duct of constant cross section, the pressure at the exit can be expressed as

$$\frac{p}{p_0} = \left[\frac{\frac{2}{\gamma-1} + (A-U)}{\frac{2}{\gamma-1} + 1}\right]^{\frac{2\gamma}{\gamma-1}} \tag{11}$$

where p_0 is the reference pressure and γ is the ratio of specific heats of the gas (21). Eiber (18) drew an analogy between flow from an open duct and a crack propagating in a pipe. The pressure front propagation velocity (a-u) was assumed to be equivalent to the crack propagation velocity (v) and the pressure at the crack front equivalent to p of expression 11. p_0 was taken to be the initial static line pressure and a_0 the sonic velocity for the initial static conditions. This resulted in an expression between pressure at the crack front and crack velocity (22) as given by

$$\frac{p}{p_0} = \left[\frac{\frac{2}{\gamma-1} + \frac{v}{s_0}}{\frac{2}{\gamma-1} + 1}\right]^{\frac{2\gamma}{\gamma-1}} \tag{12}$$

When the crack velocity is greater than the sonic velocity of the gas, the pressure at the crack front is simply the static line pressure. Eiber presented these results graphically for natural gas which has a ratio of specific heats of 1.3. Eiber's results are presented along with the curve for nitrogen, which has a γ value of 1.4, in figure 6.

Pressure decay measurements made in the Battelle Line pipe

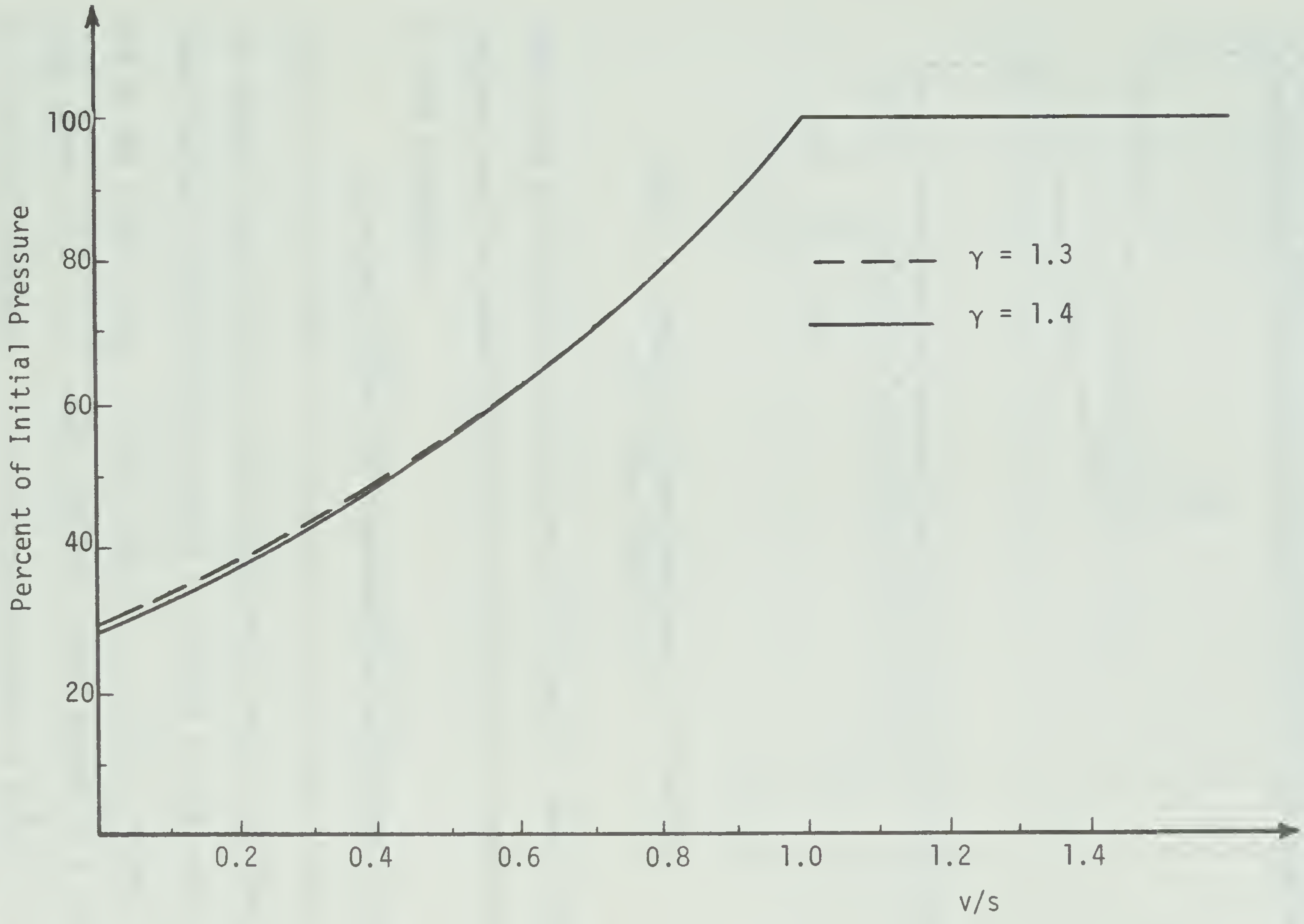


Figure 6 Pressure Correction for Propagating Cracks in Pipelines

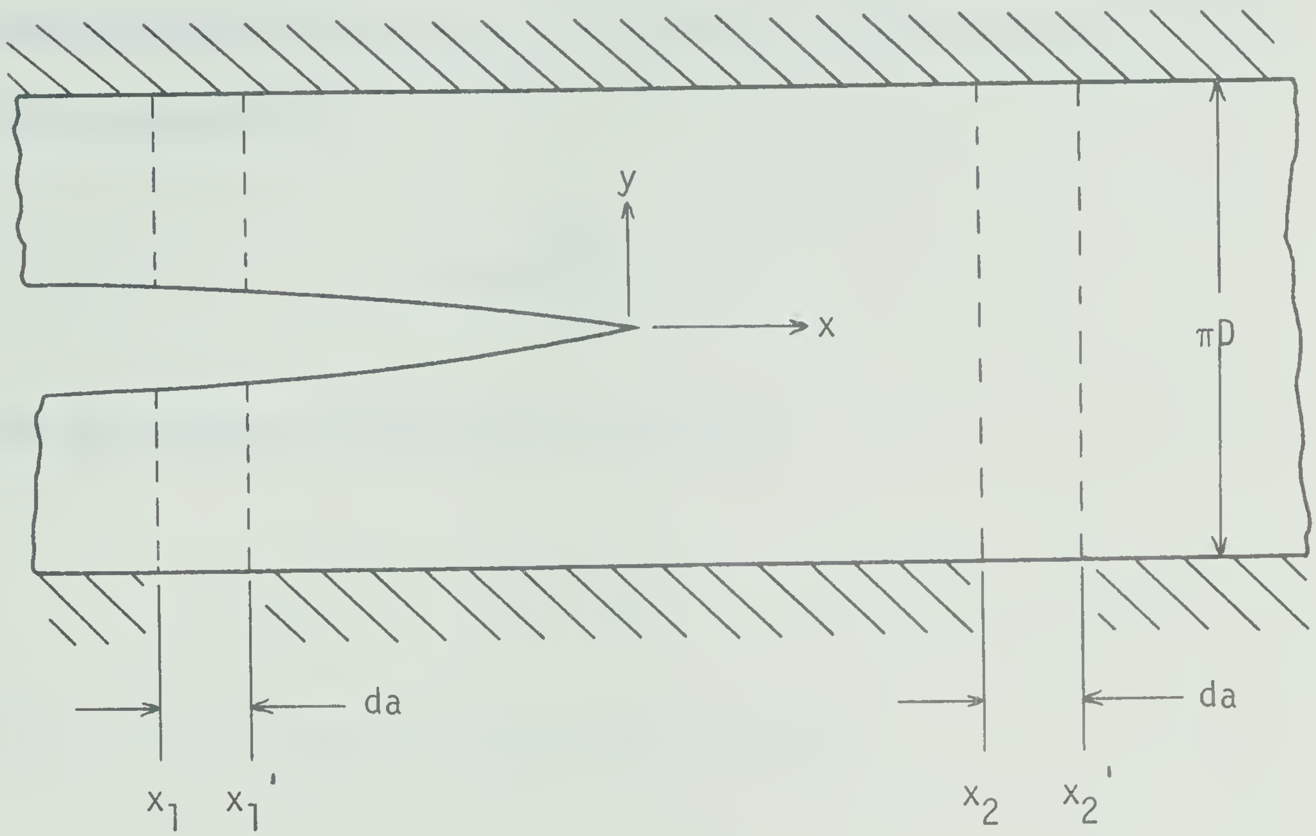


Figure 7 Model of a Long Fracture in a Pipeline with a Hoop Stress of σ

study show an excellent correlation with figure 6. Maxey (22) cautions that the above theoretical consideration is applicable only to long fractures.

Irwin and Corten (23) presented the derivation of an expression for the effect of a long crack in a cylinder (figure 7). The dashed lines x_1 and x_2 are located sufficiently far from the crack tip such that the stress field is uniform to the left of x_1 and to the right of x_2. To the right of x_2, where σ_y equals the hoop stress, the strain energy per unit crack length is $\frac{1}{2}\sigma\varepsilon B$ where B is the wall thickness. This can be rewritten as $B\sigma^2/2E$. To the left of x_1 the strain energy is zero. The crack advances a distance

da. The conditions which existed at x_1 and x_2 prior to the crack advance exist at x_1' and x_2'. The loss in strain energy for the crack advance da is

$$\delta U = \frac{B\sigma^2}{2E} (\pi D \, da)$$

The new fracture surface area created is

$$\delta A = B da$$

Therefore, the strain energy release rate is

$$\mathcal{G}_c = \frac{\partial U}{\partial A} = \frac{\pi D \sigma^2}{2E}$$

The stress intensity factor, K_c, is determined with the aid of expression 4;

$$K_c = \sigma_c \sqrt{\frac{\pi D}{2}} \quad \text{or} \quad K_c = \sigma_c \sqrt{\frac{\pi D}{2} (1-\nu^2)} \tag{13}$$

For small axial flaws, the effect of the flaw can be approximated by Griffith's equation,

$$\sigma_c = \frac{K_c}{\sqrt{\pi a}} \tag{14}$$

It is not unreasonable to expect that as the crack length increases with respect to the diameter of the pipe, the effect of the finite length in the hoop direction will introduce error. It can be assumed that when the crack length is smaller than the pipe diameter, the Griffith expression describes the effect of the flaw. If the crack length is greater than the pipe diameter, the effect of the flaw is independent of the flaw length and determined by expression (13).

The application of the fracture mechanics approach to fracture in line pipe may be complicated by the fact that as well as a hoop stress, there may be a bending stress as a result of an outward bulging in the area of the crack. This bending stress, superimposed on the in-plane hoop stress, will tend to produce a higher stress at the outer face of the pipe. Hahn, Sarrate and Rosenfield (24) have corrected for this effect by expressing the critical hoop stress for crack extension in terms of the nominal stress for crack extension in a flat plate. To date, however, such a correction has not been applied to line pipe studies. Equation (13) provides the most common form of analysis (18,19,20,23,25).

2.4 Specimen Design

There are many sources of error in testing for fracture toughness data. The most critical aspect of toughness testing is specimen design. The validity of toughness data is dependent on the ability of the test specimen to simulate the stress field of the

flawed structure. Thickness, crack length and proximity of stress free boundaries must be duplicated by the specimen. Irwin and Kies (26) point out that fracture mechanics assumes that any two systems for stressing a crack are equivalent only if they produce the same stress environment near the leading edge of the crack. In the case of notched specimens, the notch root area represents the leading edge of a crack. Since the root radius of a real crack is very small, the root radius of the notch should be kept as small as possible. Specimens may be precracked by the application of cyclic stresses in an attempt to duplicate a real flaw. This technique has been applied to Charpy V-notch, slow bend and double cantilever beam specimens (27,28,29). If the notch root radius of the specimen isn't sufficiently small, there may exist a barrier to crack initiation with the result that the measured initiation toughness will be high (30). This barrier to crack initiation seems to result from plastic flow at the notch root which has a tendency to blunt the notch and produce an apparent increase in the critical stress intensity factor.

2.5 Fracture Control

One technique of fracture control, proof testing, employs the crack blunting technique. The proof stress appears to cause the ends of the flaw to yield with the result that a favorable residual stress is left about the flaw. In steel line pipe, Duffy (31) has applied proof stresses as high as 122 percent of specified minimum yield strength. It is important to note that the higher the proof

stress, the smaller will be the minimum size of flaw affected, but the greater will be the danger of failure during testing. Unfortunately, this technique will not eliminate slow crack extension due to fatigue or stress corrosion. There are numerous reports of failure in which the stress at failure was considerably below the proof stress or a previous service stress (23).

As a result of the Polaris rocket motor case failures, Irwin (32) developed the leak-before-break toughness criterion. It requires that the material have sufficient toughness to prevent the propagation of a through wall crack of length equal to twice the wall thickness when the yield stress is applied. An expression for the stress intensity factor for small scale yielding can be obtained by applying a plastic correction to the crack length in Griffith's equation. This yields

$$K^2 = \frac{\pi\sigma^2 a}{1 - \frac{1}{2}\left(\frac{\sigma}{\sigma_Y}\right)^2} \tag{15}$$

Apply the leak-before-break criterion by letting $\sigma = \sigma_Y$, $a = B$ and $K = K_c$. Therefore,

$$K_c^2 = 2\pi\sigma_Y^2 B \tag{16}$$

Expression (14) was,

$$\sigma_c = \frac{K_c}{\sqrt{\pi a}} \tag{14}$$

Using expression (14) and (16), β_c is found to be,

$$\beta_c = \frac{1}{B}\left(\frac{K_c}{\sigma_Y}\right)^2 = 2\pi \tag{17}$$

Therefore β_c must be greater than or equal to 2π in order that the leak-before-break be met.

The ideal approach to fracture control involves a thorough examination of the complete structure for flaws. The critical stress intensity factor, K_{IC}, permits the determination of the allowable flaw size. During service periodic inspection is required to insure that no slow crack growth occurred. For many applications, the expenses involved in applying this technique of fracture control may not be justified.

CHAPTER III

EXPERIMENTAL TEST METHODS

3.1 Material Properties

To study the fracture toughness of polyvinylchloride pipe, it was required that the Modulus of Elasticity, E, and Poisson's Ratio, ν, be known. A four point bend test was used to determine the Modulus of Elasticity. A length of pipe was simply supported and equal forces applied at the quarter points as shown in figure 8. The deflection measured at the midspan together with the theoretical expression for deflection (expression 18) permitted an evaluation of E.

$$\delta = \frac{11}{384} \frac{F\ell^3}{EI} \tag{18}$$

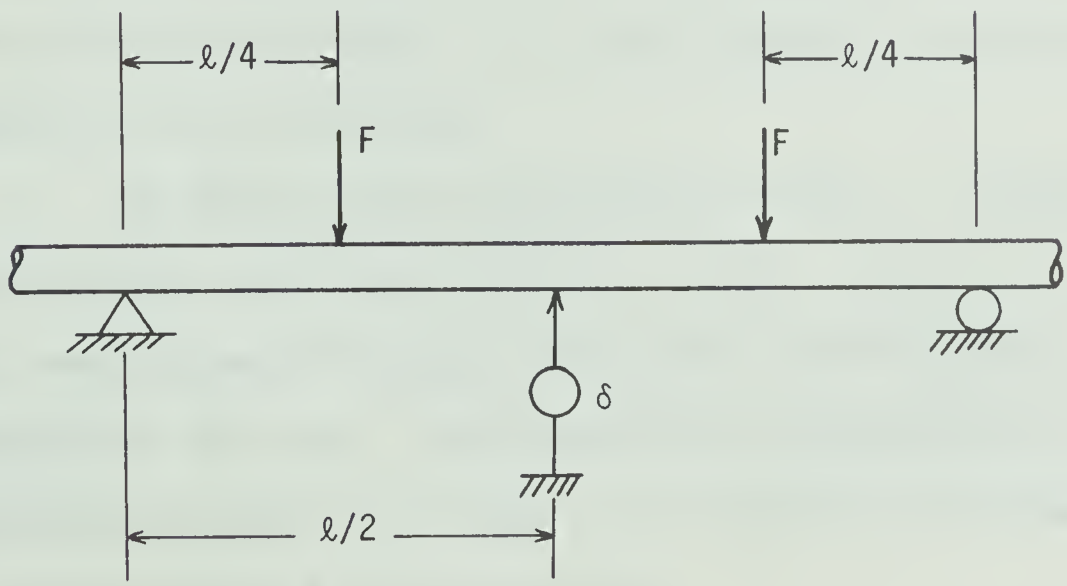


Figure 8 Four Point Bend Test

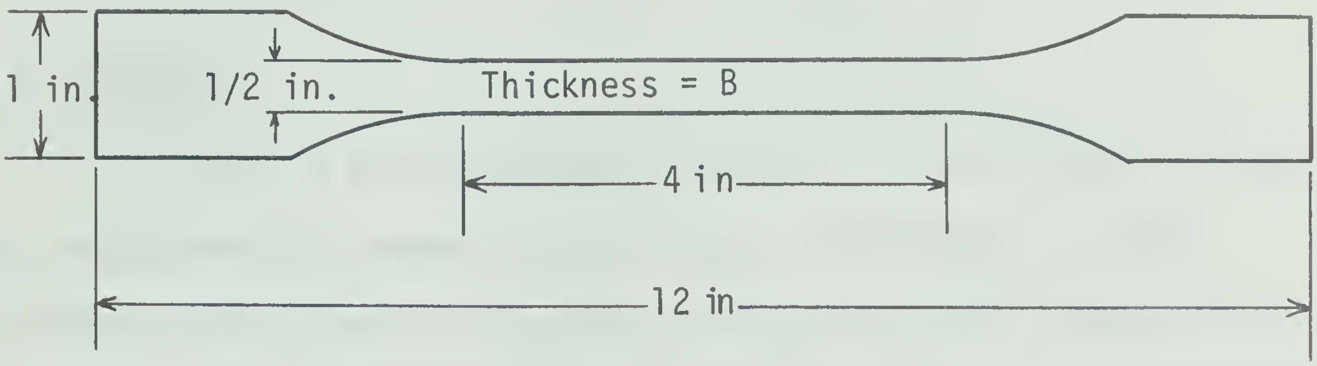


Figure 9 Tensile Specimen

This method indicated values of E ranging from 410,000 p.s.i. to 460,000 p.s.i. (Figure A1, A2, A3).

A twelve inch long tensile specimen was cut from the pipe. The ends were flattened with heat but the narrowed portion, on which two longitudinal strain gauges were mounted, was left curved (figure 9). The slope of the tangent of the stress strain curve (figure A4) at a low stress was taken to determine the modulus of elasticity (A.S.T.M. D638). This test indicated a yield stress of 6000 p.s.i. at a 0.2% offset.

In order to determine Poisson's Ratio, ν, a twenty inch length of pipe was loaded axially in tension. Eight strain gauges were equally spaced in groups of two about the circumference at the midlength of the pipe. Each group had one longitudinally and one transversely mounted strain gauge. The results of this test indicated a ν value of about 0.375 (figure A5).

A conservative value of E of 400,000 p.s.i. was chosen for polyvinychloride. The results for these tests are presented graphically in Appendix A.

3.2 Specimen

Since it was considered preferable not to flatten the pipe wall with heat the common test specimens (notch bend or double cantilever beam) could not be used. Also, since this material behaves in a brittle fashion only at high strain rates, any test which results in low strain rates could not be employed. An attempt was made to use a double cantilever beam specimen. This test was expected to produce a series of run-arrest type fractures which would most likely be brittle. However, the specimen produced a slow tearing fracture. There also was difficulty in producing and loading a curved double cantilever beam specimen from 1-1/4 inch diameter pipe.

It was decided that a length of pipe be burst with a compressed gas in a manner similar to that in which the Battelle line pipe tests were conducted (18,19,20). This approach appeared particularly attractive because the actual conditions of fracture could be closely simulated and any errors introduced as a result of specimen design could be avoided. The specimen was 1-1/4 inch diameter pipe, the same as the service failure.

The test section was isolated in a separate room. The pressure, provided by a high pressure gaseous nitrogen bottle, was controlled by a pressure regulator. Near the pressure regulator, a

bleed down valve was included in order that the gas could be released in the event that the specimen did not fail. The fracture initiated at an artificial flaw which varied in length from two to six inches. The material remaining in the root of the flaw varied from about 0.005 to 0.015 inches, depending upon the desired burst pressure.

3.3 Unconstrained Specimen

A number of specimens were tested without any confinement to the radial expansion of the pipe wall. In order to prevent excessive scatter of debris, a wire mesh was laid over the specimen. These tests were unsatisfactory because the direction of fracture propagation appeared to be random resulting in a line pressure drop and crack arrest. It was apparent that the lack of confinement resulted in such high radial deflections at rupture that the pipe fragmented (figure 10).

3.4 Pipe Constrained Specimens

In an attempt to simulate the confinement of burial in soil, the pipe was inserted in a length of steel tubing as shown in figure 11. With this technique, single fractures the length of the enclosing tube could be readily produced. As well as confining the radial deflection of the fractured pipe, the enclosure straightened the pipe. It was observed at this point that the fracture propagated preferentially on the compression side of the pipe. Occasionally there was evidence of a sine wave fracture, but this usually resulted in no more than three small amplitude waves.

Figure 10 Unconstrained Fracture Fragments

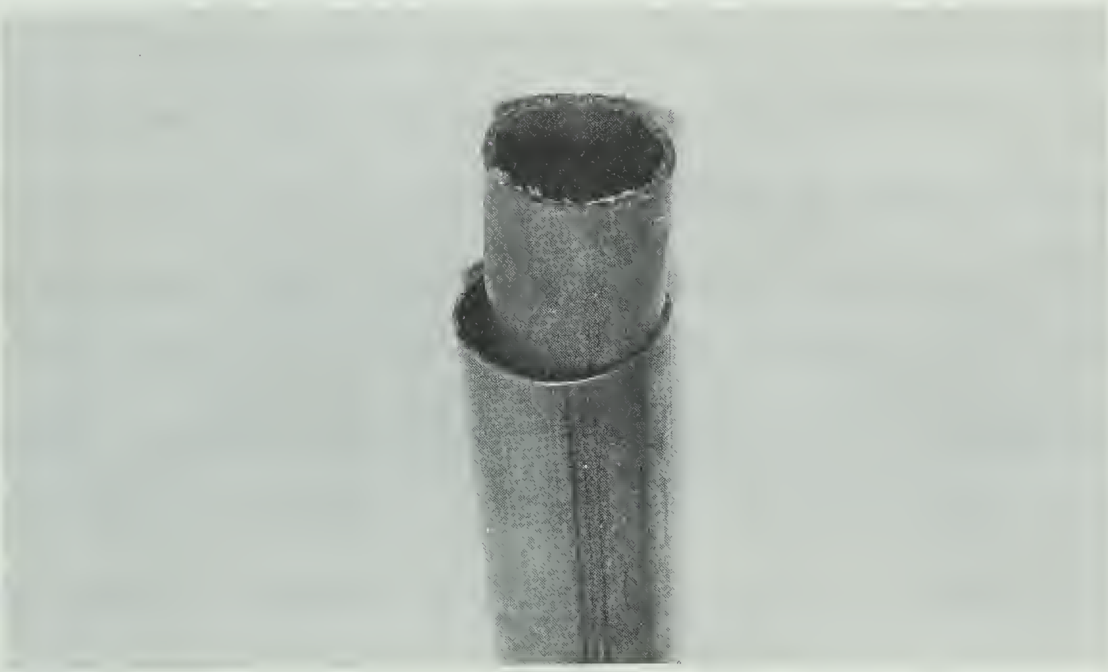


Figure 11 Pipe Constrained Specimens

As a result of the crack opening, the outer wall of the plastic pipe was scored by the inner surface of the steel tubing. The scoring suggested that on fracture, the crack opened considerably. This prompted the testing of a number of enclosure diameters with the aim of observing a change in crack behaviour. Enclosure diameters exceeding the pipe diameter by 0.084 inches, 0.109 inches and 0.209 inches were tested. Occasional fragmentation was observed with the largest enclosure. The contacting surfaces of the pipe and the steel tubing were liberally lubricated on a limited number of tests to permit free expansion of the fractured pipe.

3.5 Buried Specimens

While constraining the pipe with steel tubing showed fracture characteristics somewhat similar to those of the service failure, it appeared as though testing of the pipe under actual service conditions would be more desirable. A box, eighteen feet long, eighteen inches wide and thirty six inches high was constructed and filled with sand (figure 12). The pipe was positioned such that there was a six inch layer of sand between it and the bottom of the box. The protrusion of the pipe through the ends of the box served to anchor the pipe during backfilling. Tests were conducted with varying amounts of backfill, but a cover as low as nine to twelve inches seemed to provide sufficient constraint to radial deflection for long running fractures to occur. Test burst pressures ranged from 30 to 220 p.s.i. Generally, at pressures over 170 p.s.i. there

Figure 12 The Sand Box

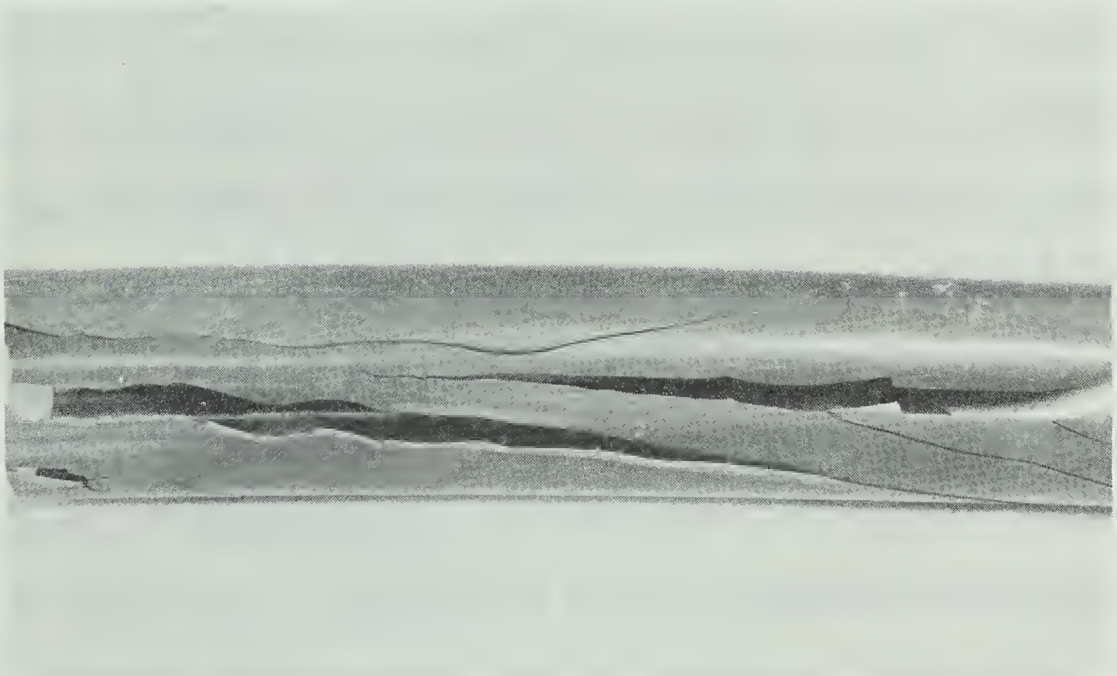


Figure 13 High Pressure Fragmentation - Sand Box

was considerable shatter (figure 13) and at pressure below 30 p.s.i. there was arrest.

It was realized that due to the restricted length of the box, end effects may have been significant. A crack velocity of one third the shear wave velocity gave a theoretical test section length, free from end effects, of one third the buried length. The test section was the middle third of the buried length.

3.6 Crack Velocity Measurement

In order to facilitate the measurement of crack velocity, a resistance drop technique was employed. The circuit is shown in (figure 14). The conducting strips were attached to the wall of the pipe. Each strip, in series with a resistor, broke with the passage of the crack. The first strip to be broken (trigger strip), associated with R_1, caused a 1-1/2 volt drop across resistor R_1. This voltage drop was used to trigger the trace on a Hewlett Packard storage oscilloscope. The size of resistors R_2 to R_6 was chosen such that the break of each successive strip resulted in a more or less even drop in voltage across R_0. The voltage across R_0 (V_0) was the vertical input to the oscilloscope. For the horizontal input, the timed sweep was used. Therefore, as a crack progressed through the strips, a stepwise trace was displayed on the oscilloscope. The time of each step, as determined by the sweep rate and the coordinates on the screen, indicated the time of rupture of each strip. By measuring the distance between each strip, the crack velocity could be

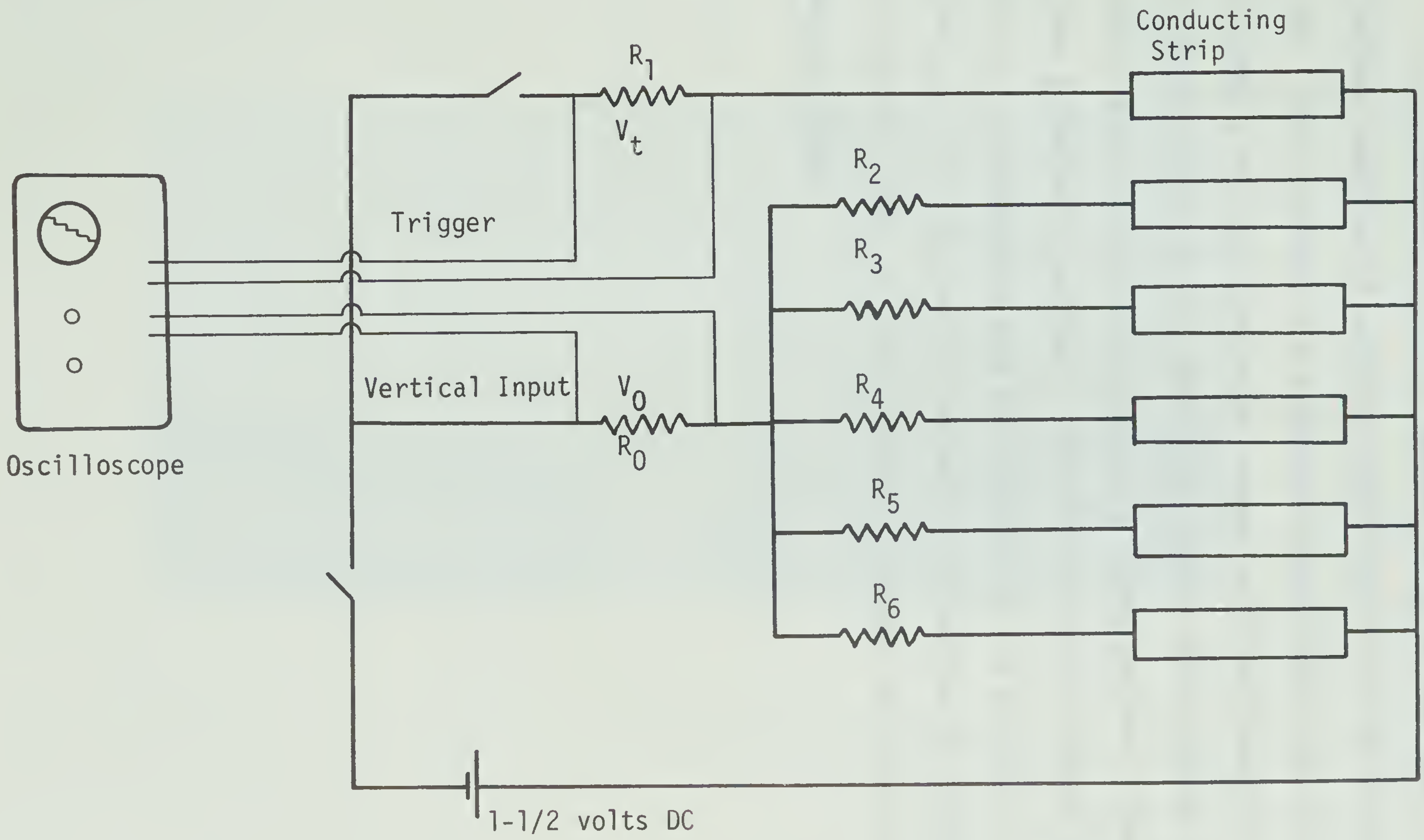


Figure 14 Crack Velocity Measurement Circuit

evaluated with an accuracy of five per cent.

Two different types of conducting strip were used. The first method consisted of painting conducting ink on the surface of the pipe. This technique was abandoned because there was difficulty in providing a reliable electrical contact with the conducting ink. In the second technique, the conducting strips were aluminum foil. The strips measured 3/16 of an inch by 3 inches and had a three inch wire lead soldered to each end. Each foil strip was centred on a piece of 1/2 inch masking tape and fastened to the surface of the pipe (figure 15). This method proved very effective as evidenced by the fact that only one strip failed to operate in the entire sequence of tests.

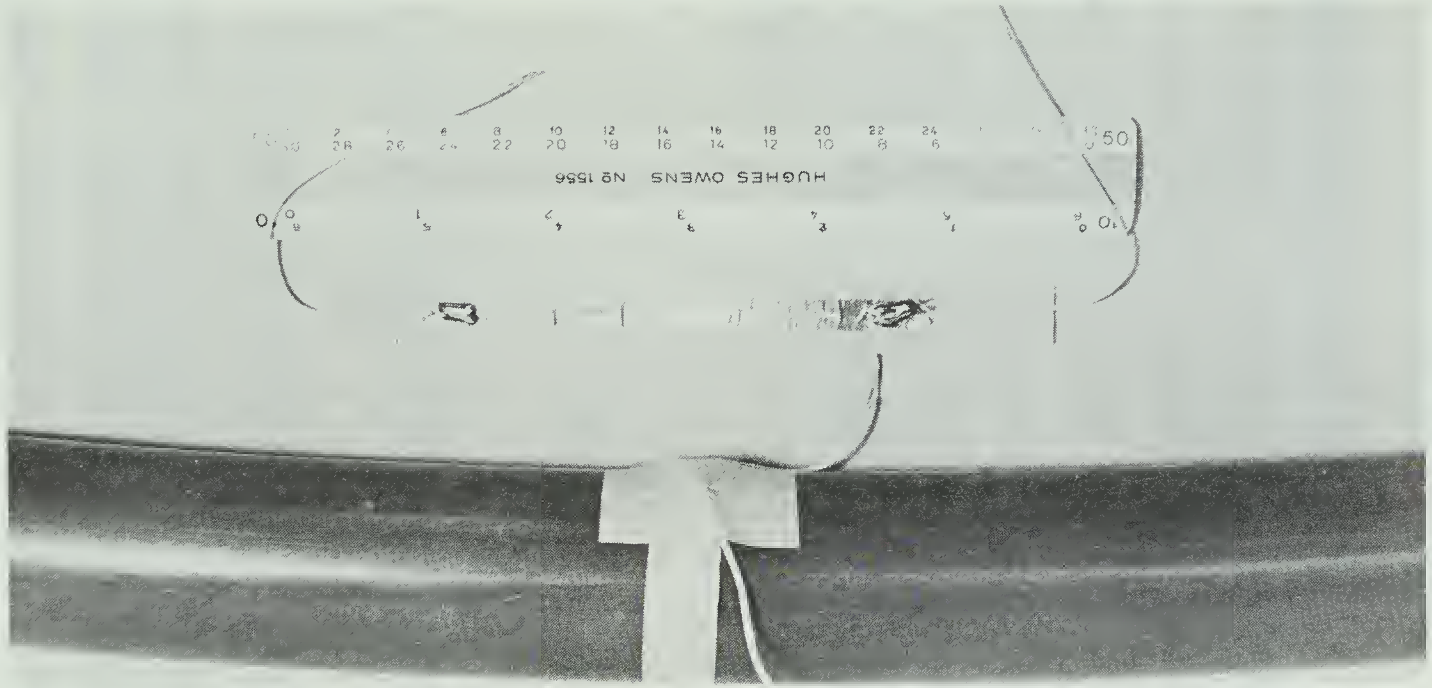


Figure 15 Crack Velocity Timing Strip

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Velocity-Toughness Relationship

All velocity toughness data was obtained from buried specimens. The crack velocity measurements indicated a linear relationship between fracture stress and crack velocity. The fracture stress for crack velocities less than sonic velocity of the pressurizing gas were corrected for with the use of figure 5. For a long propagating crack fracture toughness and fracture stress are related by expression 13

$$\sigma_c = \frac{K_c}{\sqrt{\pi \frac{D}{2}}} \tag{13}$$

The results of the velocity-toughness data are presented graphically in figure 16.

The conclusion that fracture toughness is related to crack velocity seems to oppose the results of Eiber (18). However, study of Eiber's data reveals that no correction was made for the stress when the crack velocity was less than the sonic velocity of the gas. Application of this correction to Eiber's data results in a velocity toughness relationship similar to that obtained in this study. The

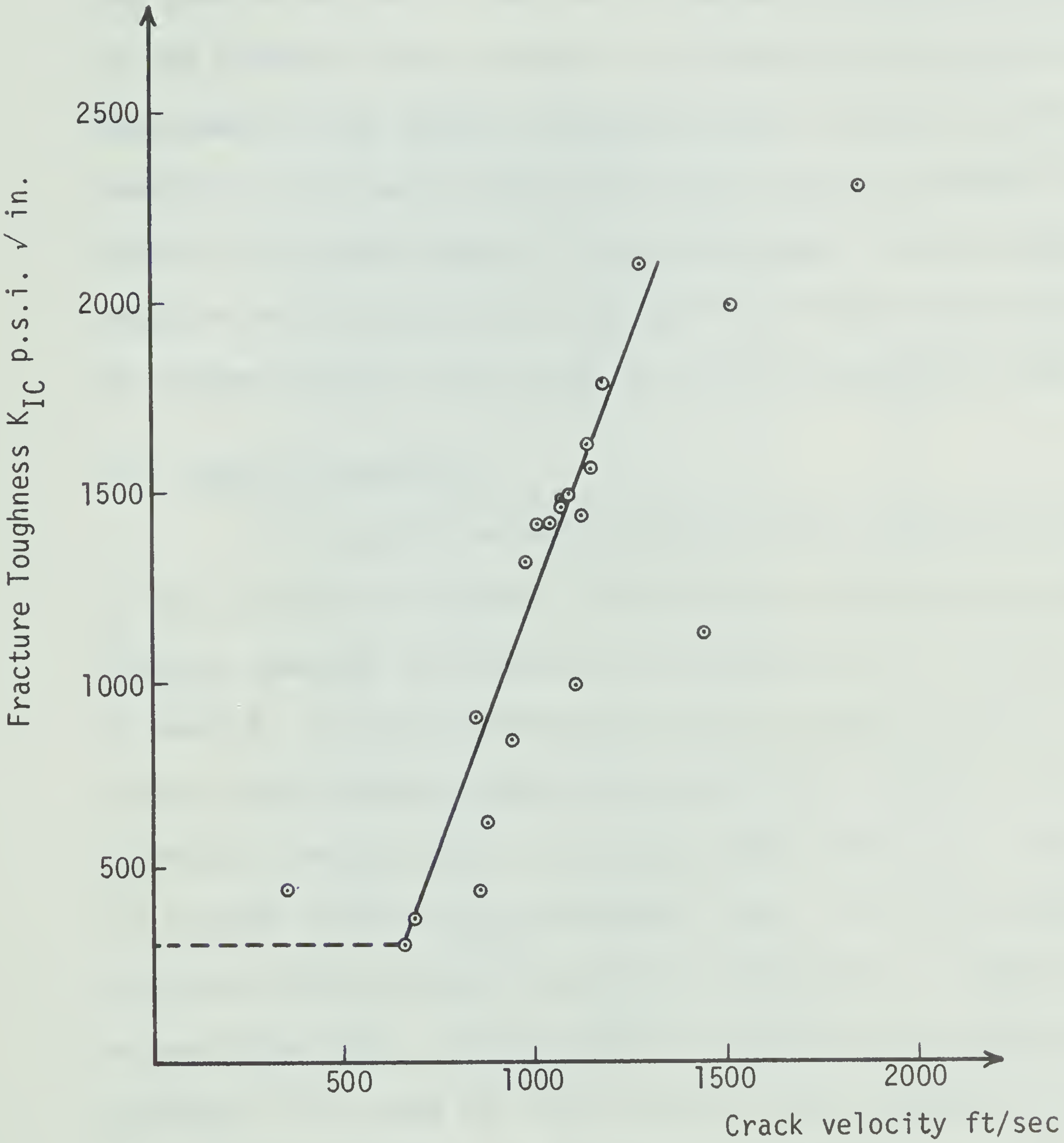
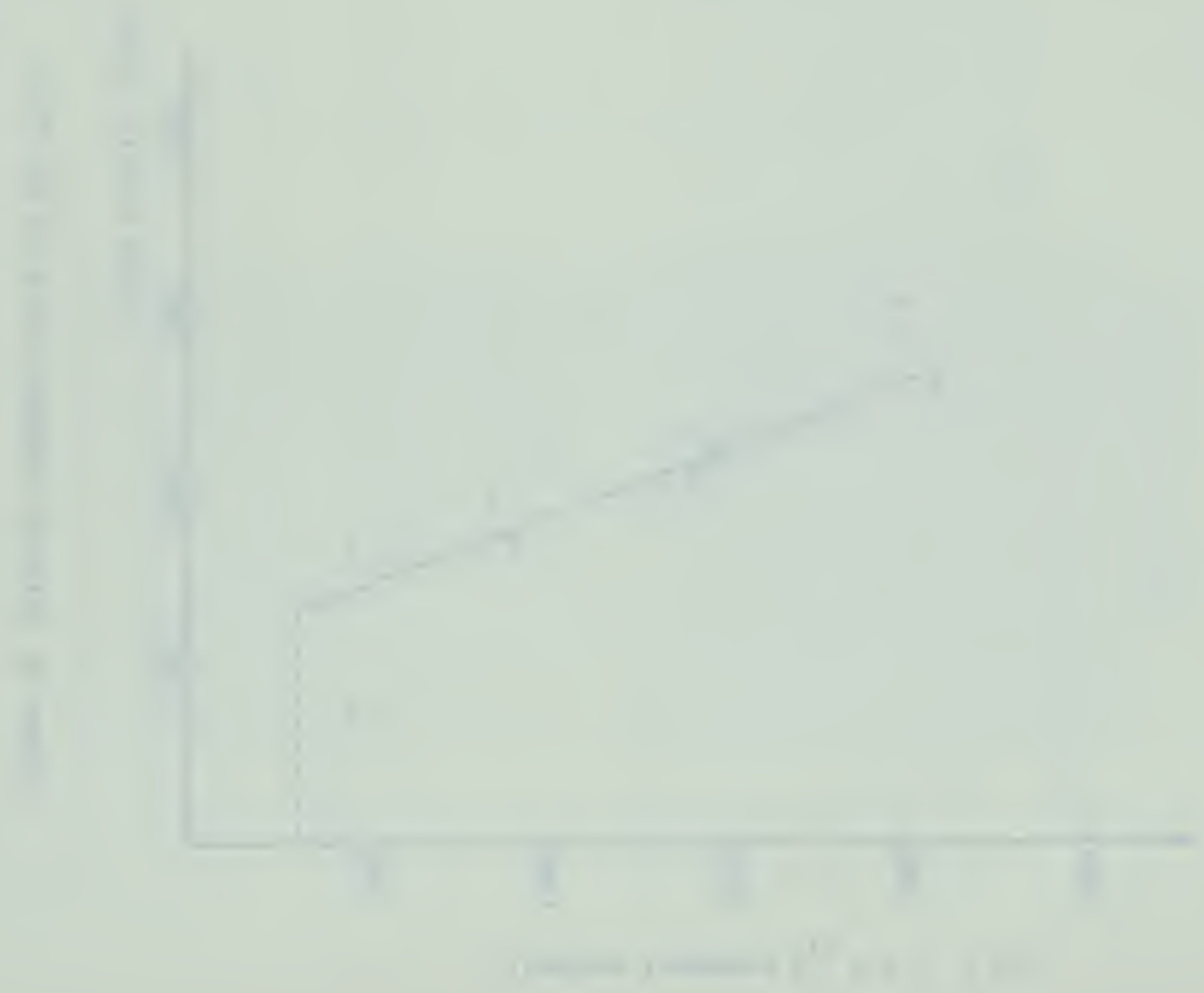


Figure 16 Velocity Toughness Curve for PVC Pipe



results of this study are very similar to those of Cotterell (15).

Sine wave fractures occurred occasionally at a stress between 1100 and 1300 p.s.i. (figure 17 compares two test specimens and the service failure). There was no change in the apparent crack velocity* at the transition from straight line fracture to sine wave fracture. Measurement of the actual crack path length indicated that the crack length of a sine wave fracture was about 15 percent greater than the straight line crack length. This would suggest that the energy dissipation for an apparent unit length of sine wave crack advance would be fifteen percent greater than for a unit straight line crack advance.

4.2 Effect of Backfill

The backfill material tended to limit the radial deflection of the pipe wall at fracture. The fact that there was no sudden pressure loss due to fragmentation allowed time for a running crack to develop. Irwin and Corten (23) have discussed the effect of a strip of wall bending outward and causing high stresses on the inner surface of the pipe wall in the longitudinal direction. This stress field tends to divert the propagating crack to the hoop direction with the result that the direction of propagation is random and pieces of wall break off. As this process is repeated, the longitudinal velocity of the crack may drop below the sonic velocity of the gas and eventual pressure loss results in crack arrest. Thus, it is suggested that in this study backfill prevented fragmentation and promoted long running fractures.

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*In this discussion, apparent crack velocity is considered to be length of pipe fractured divided by time. It is not the actual velocity of the crack in cases where the fracture is not straight and axial.

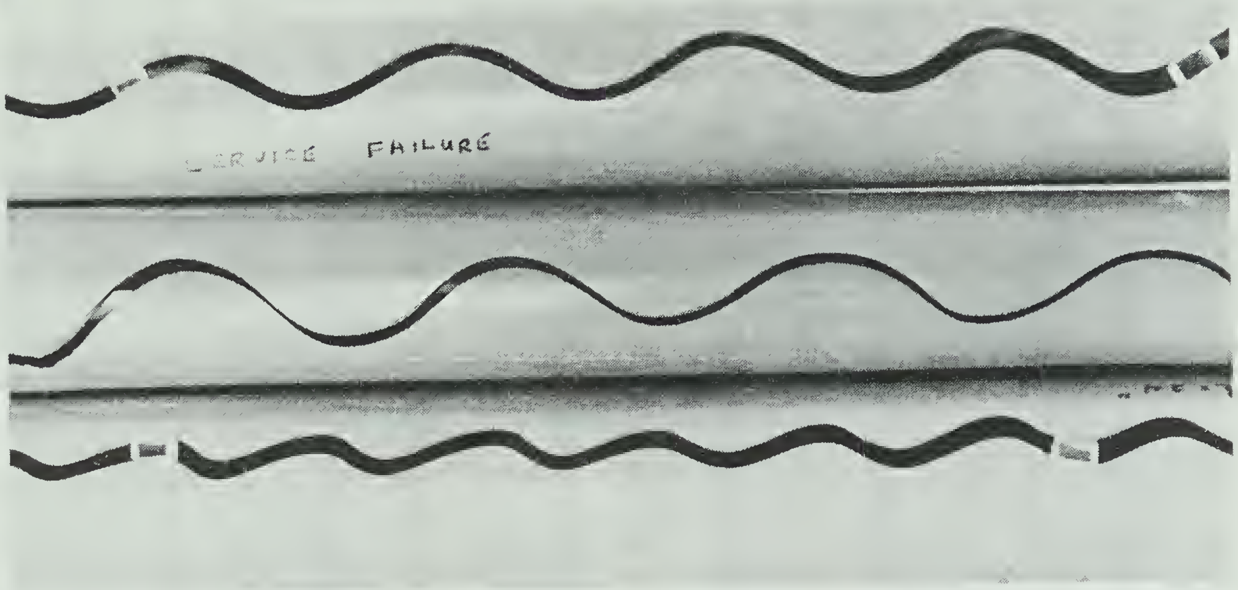

Figure 17 Sine Wave Fractures

4.3 Fracture Surface

The surface of straight line fractures at stresses between 300 and 1250 p.s.i. were very smooth and gave no indication of plastic flow. At a stress of 1600 p.s.i. there were many small fractures along the path of the main fracture which arrested after about half an inch of propagation. The fracture surface could be described as "hackled". Since a single smooth fracture will not absorb all the energy released, there is a tendency for the crack to branch into two or more cracks. The roughening of the fracture surface associated with high crack velocities may indicate that the crack is on the verge of branching.

In both the service failure and the experimental sine wave fractures, the amplitude of the wave is greater on the inner surface of the pipe than on the outer surface. This produces a fracture surface which is not normal to the wall of the pipe.

In this material it is possible to determine the direction of propagation of a sine wave fracture by the fracture surface appearance. Each wave peak exhibits a slight branching effect similar to that described for high velocity propagation. Figure 18 shows the fracture pattern and the direction of crack propagation. The crack branches point in the direction of crack propagation. The alignment of the minute arrested crack branches on the fracture surface suggests that the crack leads on the outer surface of the pipe (figure 19).

4.4 Evaluation of PVC Pipe

Reynolds (33) expressed doubt about the applicability of a critical stress intensity factor and linear elastic fracture mechanics approach to PVC Pipe. It was pointed out that for such an approach to be valid, the plastic would have to behave in a very brittle fashion. Reynolds suggested an empirical approach based on a load limit-flaw size relation would be preferable. However, since the fractures encountered in this study were extremely brittle, an attempt has been made to determine a minimum fracture toughness value.

Figure 18 Sine Wave Fracture Pattern

It has been concluded that the toughness of plastic pipe can be evaluated from the minimum effective pressure required for substantial propagation (12 inches). Crack propagation occurred at stresses as low as 200 p.s.i. Assuming this is the lowest pressure for crack propagation, the minimum fracture toughness can be determined from figure 16 as

$$K_{IC} = 300 \text{ p.s.i.} \sqrt{\text{in}}$$

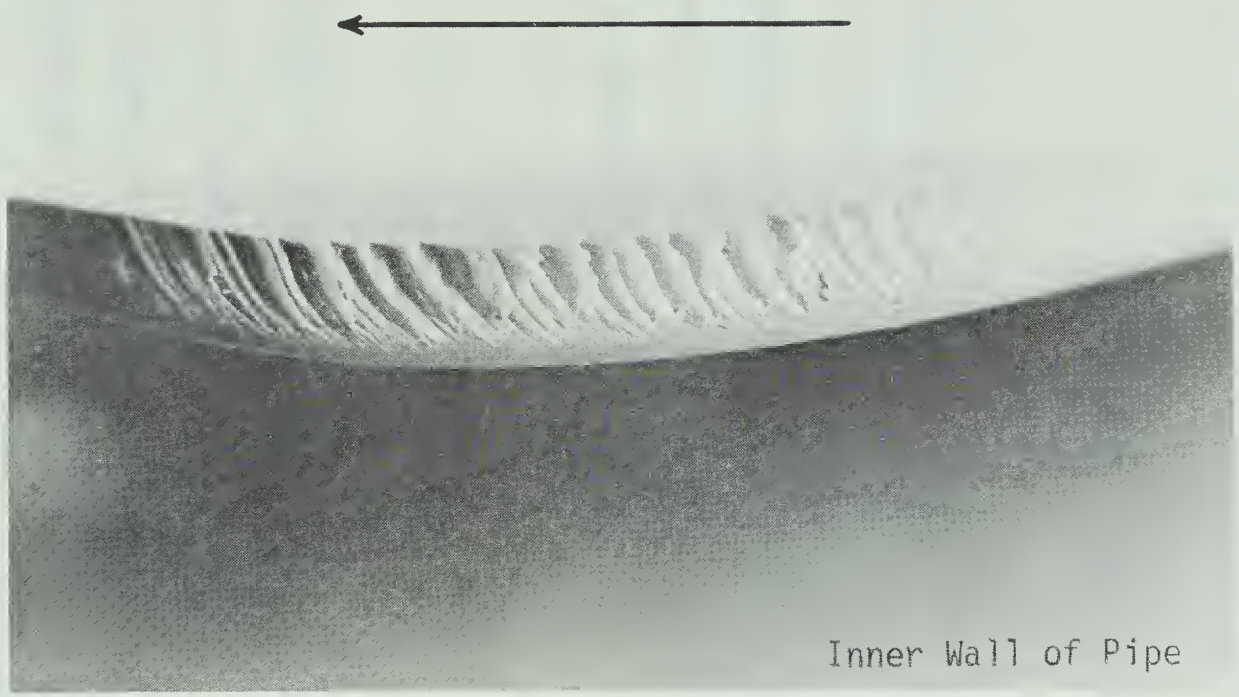

Figure 19 Surface Features of a Sine Wave Fracture

Straight line fractures were mode I fractures and the lack of any plastic deformation suggested minimum resistance to crack propagation (minimum toughness). Equation 14 permits evaluation of the maximum allowable through wall flaw length. For 1-1/4 inch diameter schedule gas plastic pipe a pressure of 65 p.s.i. causes a hoop stress of 480 p.s.i. Solving for the critical crack length gives

$$480 = \frac{300}{\sqrt{\pi a}} \quad \text{(or } a = 0.123\text{")}$$

The wall thickness of the pipe is about 0.100 inches. Considering a yield stress of about 6000 p.s.i. reveals that the material falls far short of satisfying Irwin's leak-before-break criterion. (e.g. a_c = 0.001 in.)

The minimum fracture toughness together with expression 13 can provide a design criterion for pipe.

$$\sigma_c = \frac{K_c}{\sqrt{\pi \frac{D}{2}}} \tag{13}$$

For a given material with a known critical stress intensity factor the product $\sigma_c \sqrt{D}$ must be a constant ($K_c \sqrt{\frac{2}{\pi}}$). The form of the relationship between σ_c and D is shown graphically as a family of curves in figure 20. It should be emphasized that the critical stress level for the propagation of a long crack is a function of pipe diameter. Therefore, it is impossible to assign a unique critical stress level to a material without consideration of the pipe diameter.

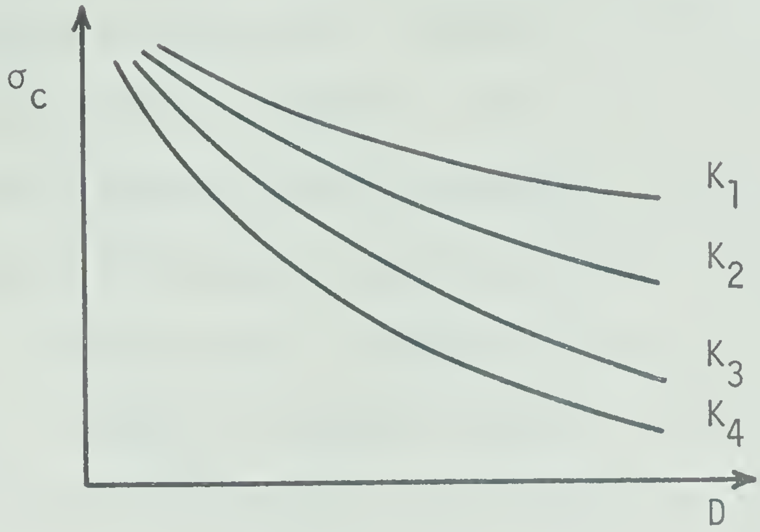

Figure 20 Graph of Critical Stress versus Pipe Diameter for Long Flaws

For design purposes, expression 13 could be rewritten as,

$$K_c = \frac{P_c D}{2t} \sqrt{\frac{\pi D}{2}} \tag{13a}$$

where P_c is the critical pressure for crack propagation. Simplifying,

$$\frac{K_c}{P_c} = 0.627 \frac{D^{\frac{3}{2}}}{t} \tag{13b}$$

The pipe diameter and the wall thickness can be related, regardless of the material, by a family of curves identified by the value of K_c/P_c as shown in figures 21, 22 and 23.

Consider a polyvinylchloride pipe, similar to that used in this study, with a minimum toughness of 300 p.s.i. $\sqrt{\text{in.}}$, a diameter

of 1.5 inches and a maximum operating pressure of 65 p.s.i. Figure 21 indicates a minimum wall thickness of about 0.25 inches. A steel pipe with a minimum toughness of 115 k.s.i. $\sqrt{\text{in.}}$, a diameter of 36 inches and a maximum operating pressure of 800 p.s.i. should have a minimum wall thickness of about 0.95 inches (figure 22).

Pipelines with diameters as large as 48 inches are now being designed. Figure 23 indicates that for this size of pipe a K_c/P ratio of 500 $\sqrt{\text{in.}}$ requires a wall thickness of 0.4 inches. Therefore, for a test pressure of 600 p.s.i., the toughness requirement of the material would be K_c equals 300 k.s.i. $\sqrt{\text{in.}}$ This material would be a much tougher steel than that presently being used in pipeline construction. For the same pipe constructed from X-60 steel, the maximum allowable hoop stress criterion requires a wall thickness of 0.25 inches. For this design by maximum hoop stress, Griffith's relation permits a maximum flaw length of slightly over 2 inches if the fracture toughness (K_c) is 115 k.s.i. $\sqrt{\text{in.}}$

Compared to design based on hoop stress and Griffith's relation, the design criterion based on expression 13 seems to require exhorbitantly large wall thicknesses. However, unlike conventional design criterion, it insures that any flaw, regardless of its length, will not propagate below the critical stress level. If Griffith's relation is employed and flaws can be detected, the critical stress level is a function of the maximum permissible flaw. In the case of plastic pipe for which no reliable flaw detection techniques are available, the criterion of expression 13a assures there will be no

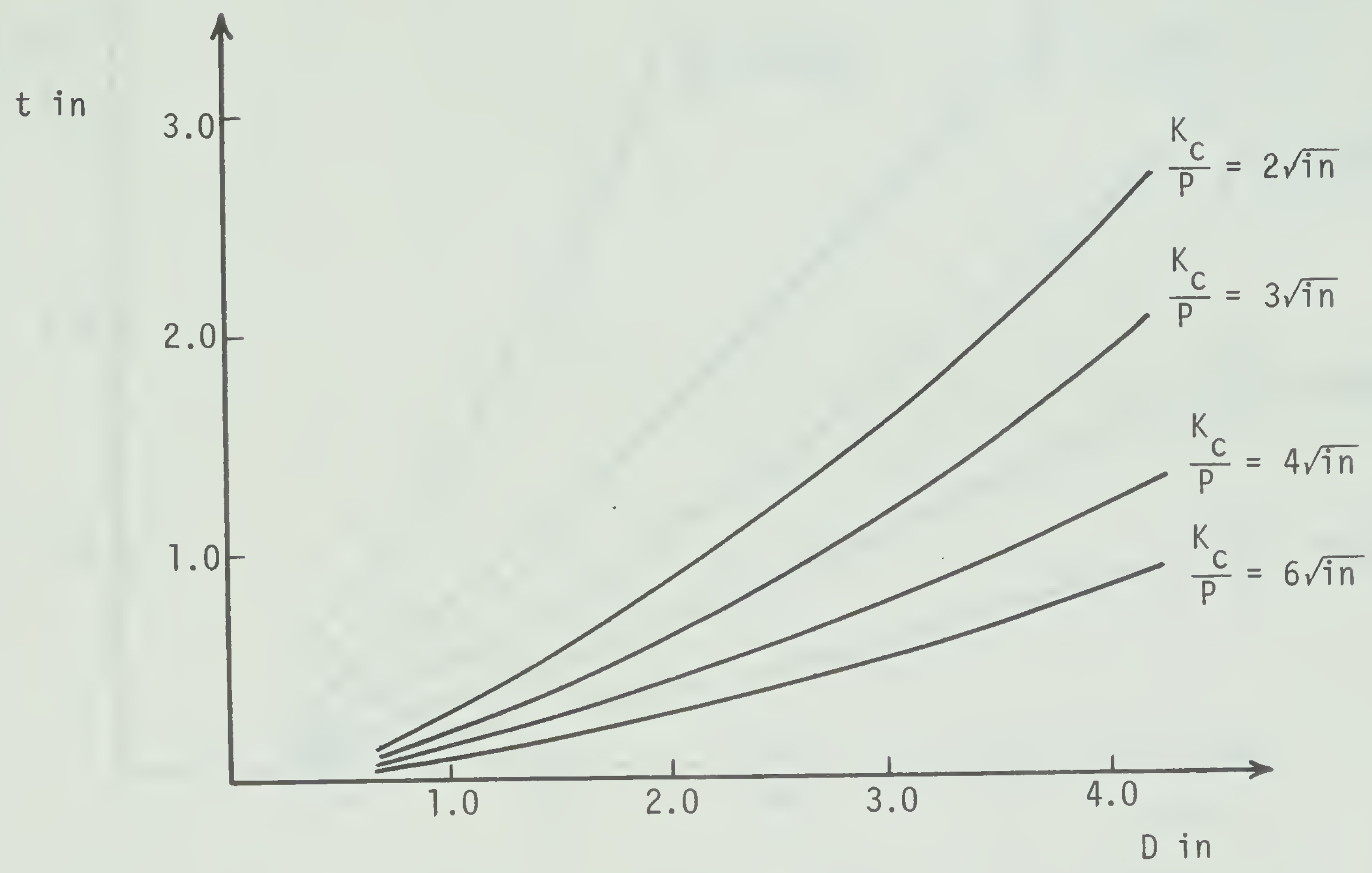

Figure 21 Design Curve for Pipe

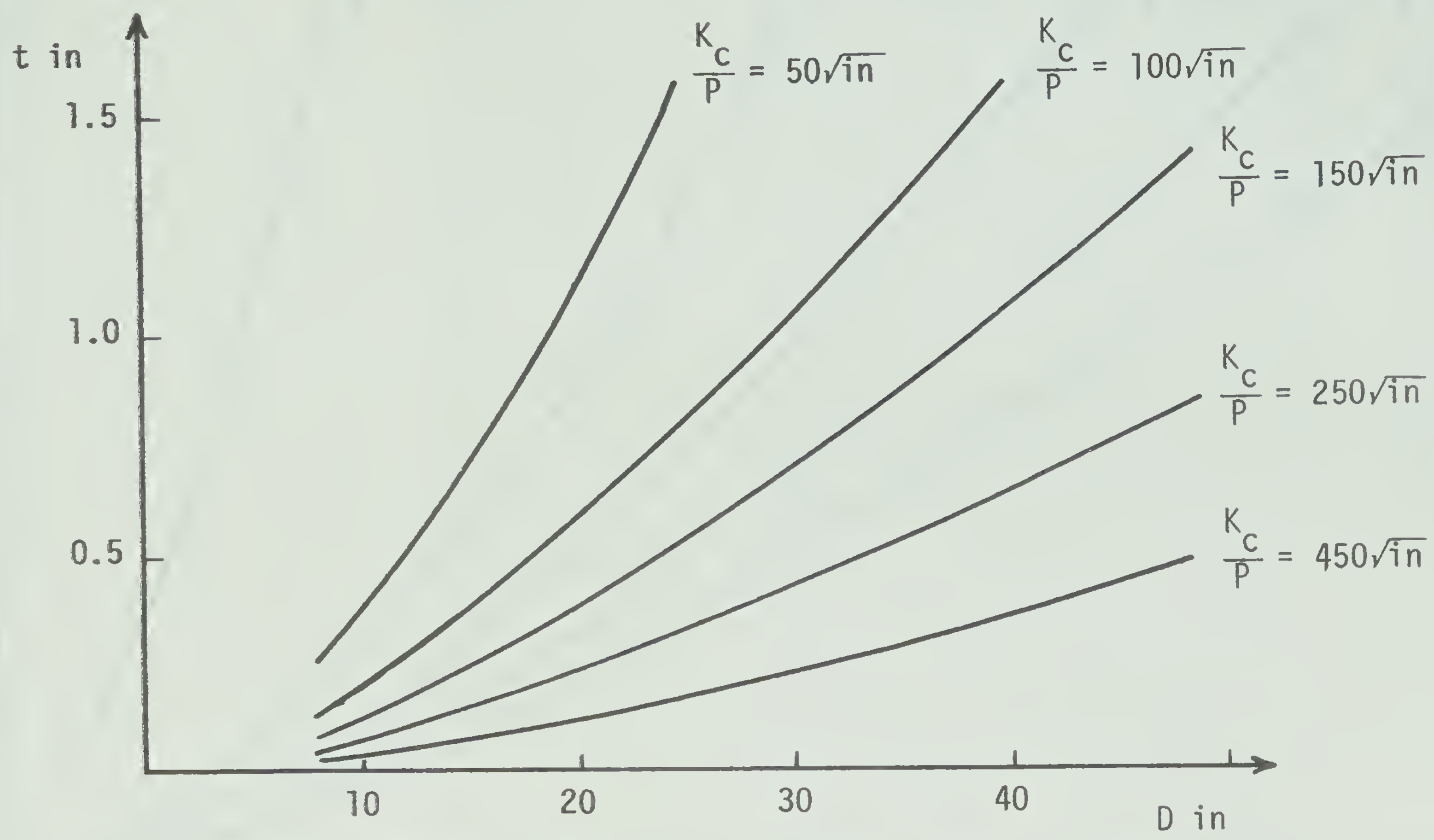

Figure 22 Design Curve for Pipe

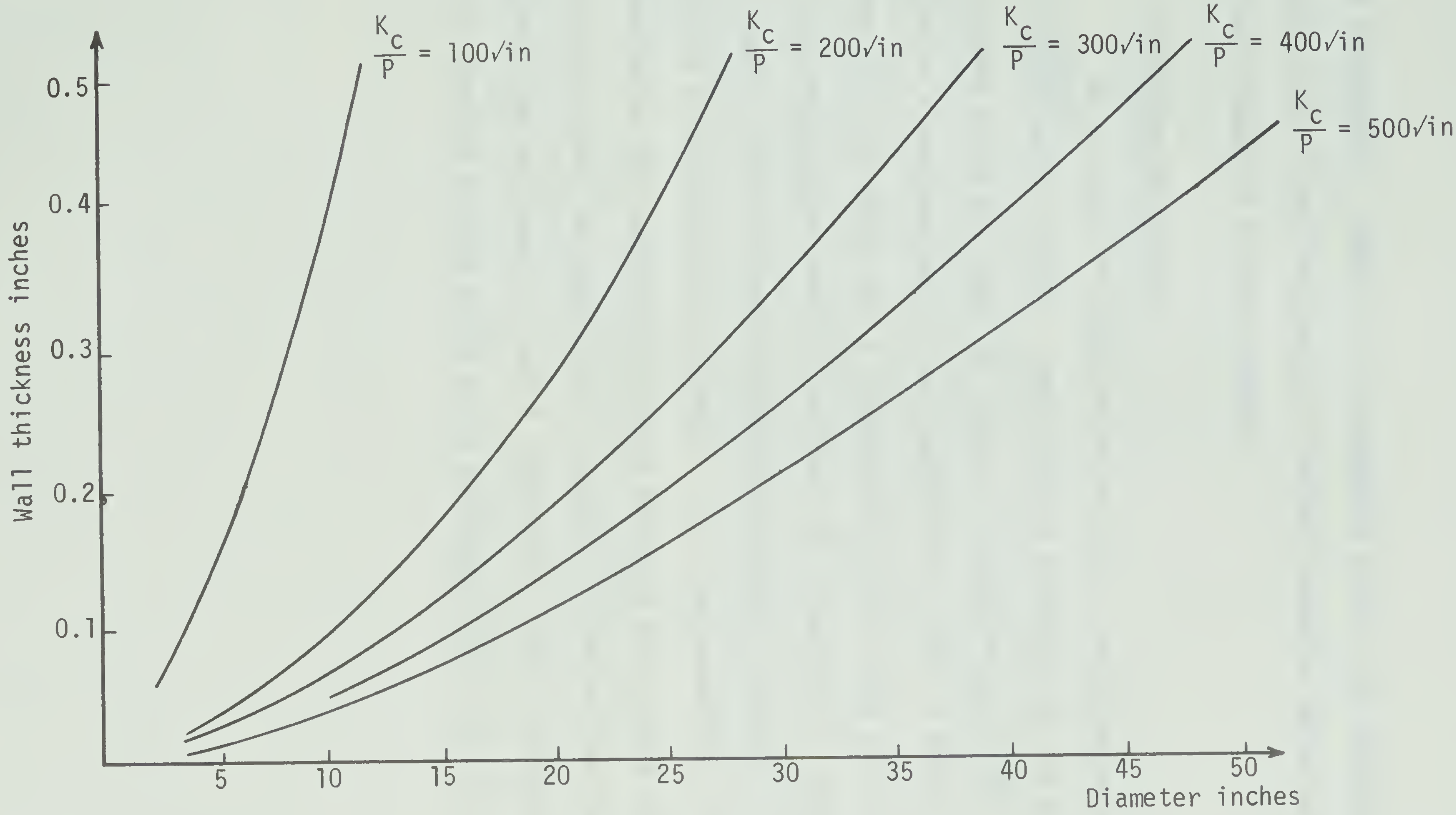

Figure 23 Design Curve for Pipe

crack propagation. Hence, it is suggested that in the absence of inspection for flaws, the design criterion presented above provides a reliable means of fracture control

4.5 Limitation of Results

As a result of being coiled on rolls, the pipe tested was not straight when unrolled. The radius of curvature of the pipe in the relaxed state was about 80 inches. Straightening of this pipe results in a maximum tensile and compressive stress of 3800 p.s.i. Svenson (34) has shown that a compressive stress along the direction of crack propagation tends to constrain the direction of propagation. For example, the direction of propagation remains parallel to the direction of the compressive stress. It is suggested that the crack propagated on the compression side of the pipe due to this effect. This implies that the properties of polyvinylchloride have been evaluated with the existence of such a compressive stress and the data can only be applied to pipe which has a curvature after uncoiling.

CHAPTER V

CONCLUSIONS

5.1 Summary

Long running fractures in polyvinylchloride pipe can be produced under laboratory conditions at room temperature. It has been demonstrated that at pressures up to 220 p.s.i. backfill plays a significant role in producing long running fractures. To a limited extent the effect of backfilling can be simulated by applying a radial constraint, such as that produced by inserting the pipe in steel tubing.

Sine wave fractures were not produced at will. However, they occurred frequently at a stress level between 110 and 1300 p.s.i. under laboratory conditions. The limited number of velocity measurements of sine wave fractures indicated no abrupt change in apparent crack velocity with the development of a sine wave fracture.

A storage oscilloscope with a voltage sensitive triggering device permits evaluation of crack velocity by a voltage drop technique. The effective hoop stress was used for cases in which the crack velocity was less than the sonic velocity of the pressurizing gas. This resulted in a linear relationship between fracture toughness and crack velocity for the range of velocities obtained. The minimum fracture toughness can be evaluated by determining the minimum stress

for significant crack propagation without determining the Modulus of Elasticity. With some development, enclosing plastic pipe in steel tubing and measuring crack velocity should prove to be a reliable technique for industrial evaluation of toughness.

A knowledge of minimum toughness and stress level determines the critical crack length. At this time, the limitation of this approach lies in the ability to locate flaws in plastic pipe. However, a design criterion was suggested which permits any length of flaw.

5.2 Suggestions for Further Study

A number of pipe-constrained specimens were tested at temperatures below 0°F. There appeared to be no change in fracture behaviour at these lower temperatures. However, a thorough study of fractures at lower temperatures could be conducted to verify this observation.

In order to better simulate an infinite pipeline, a pressure reservoir could be included in the apparatus. It would help eliminate pressure loss in fractures whose velocity is less than the sonic velocity of the gas. This would also permit shorter specimen length.

It would be interesting to study the velocity variation of a sine wave fracture. The fracture surface suggests that the velocity at the wave peaks is very high. However, it would be necessary to produce sine wave fractures consistently to conduct such a study. No reliable method was found to produce sine wave fractures in this study.

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APPENDIX A

The mean diameter of the 1-1/4" pipe tested was 1.566 inches. The average wall thickness of the pipe was 0.100 inches although it was specified as being 0.090 inches.

The cross sectional area of the pipe could be determined from

$$A = 2\pi r_m t \tag{8}$$

and the second moment of area from

$$I = \pi r_m^3 t \tag{9}$$

where r_m was the mean radius. The computed values for area and the second moment of area are

$$A = 0.492 \text{ in.}^2$$

$$I = 0.148 \text{ in.}^4$$

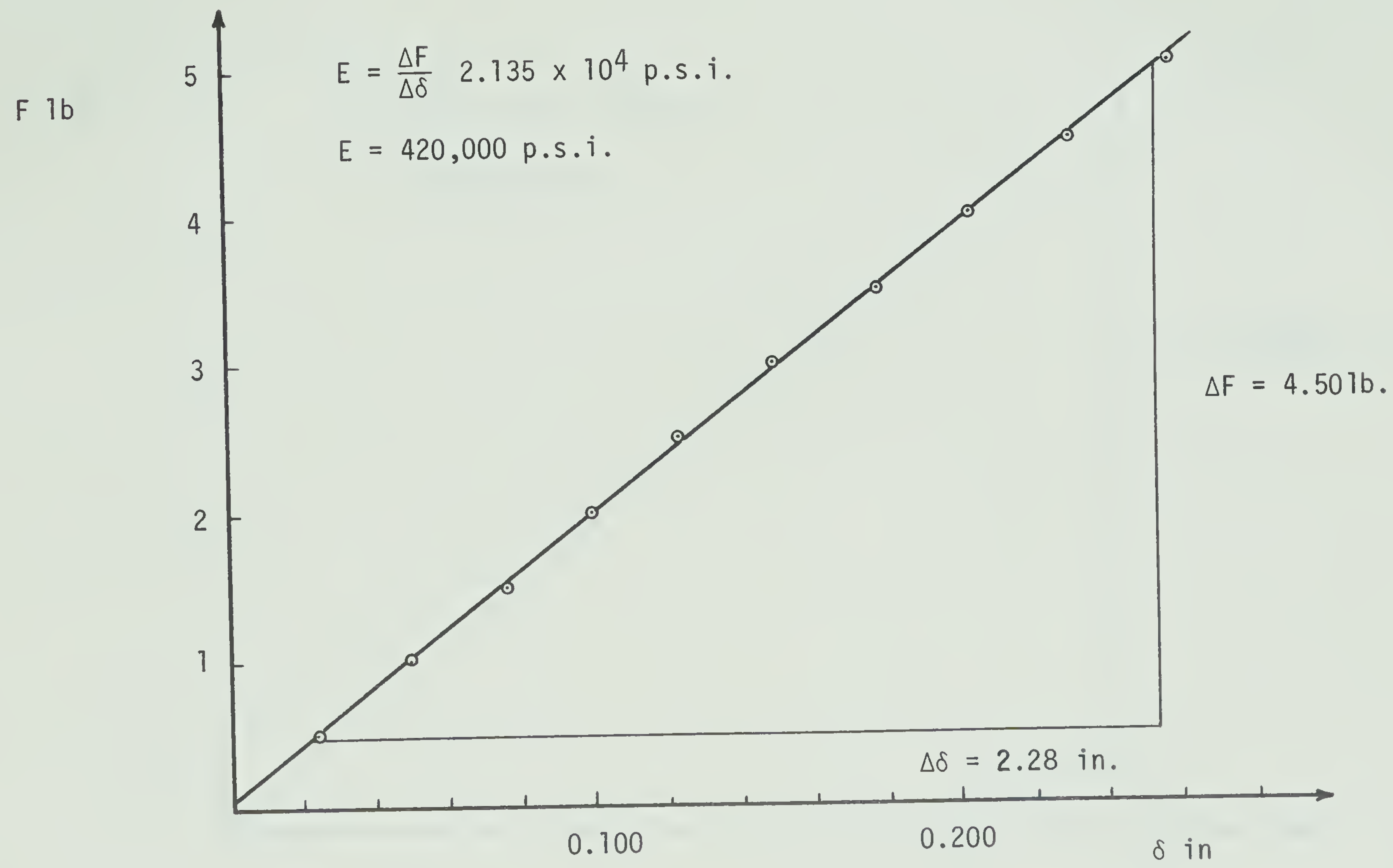

Figure A1 Four Point Bend Test

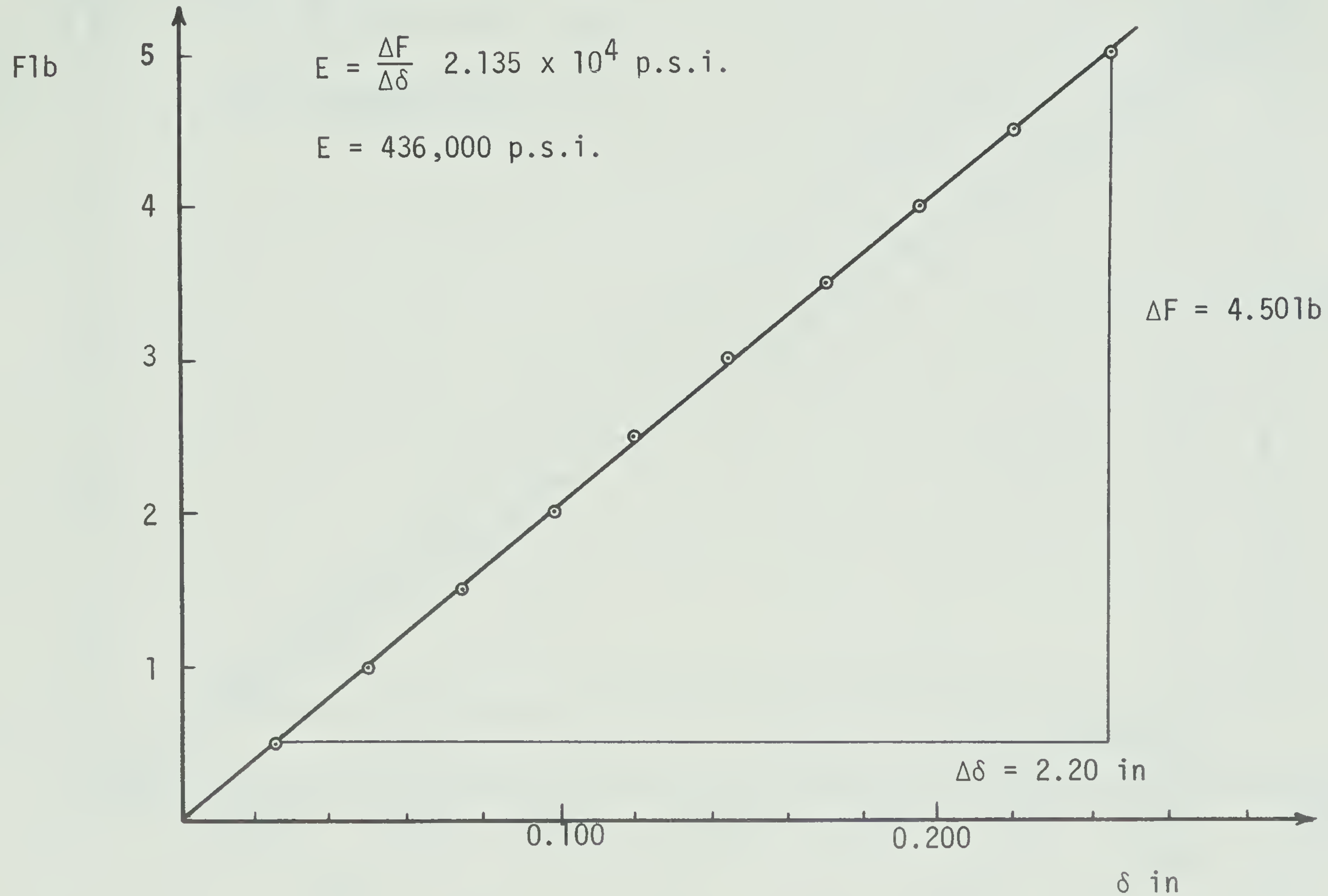

Figure A2 Four Point Bend Test

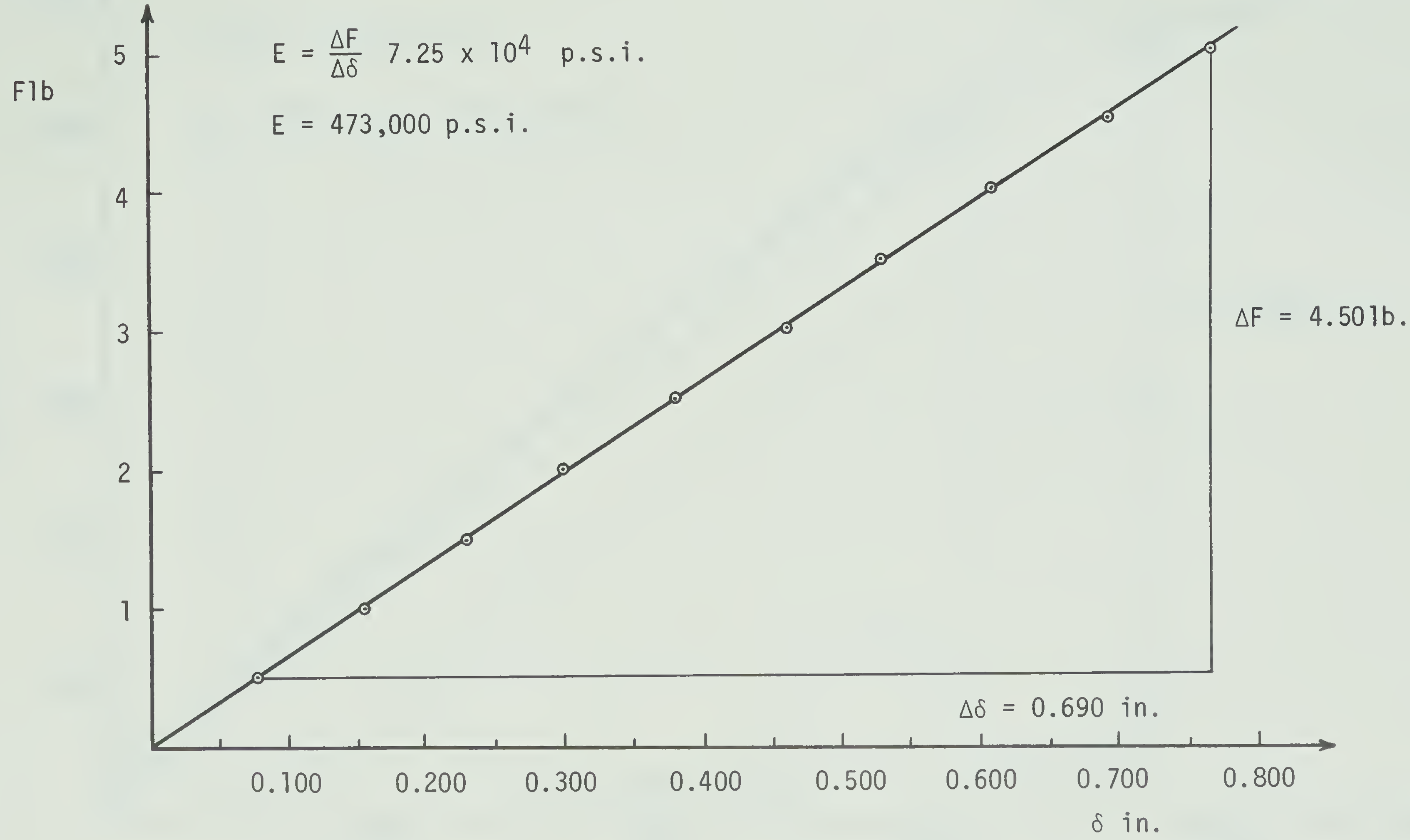

Figure A3 Four Point Bend Test

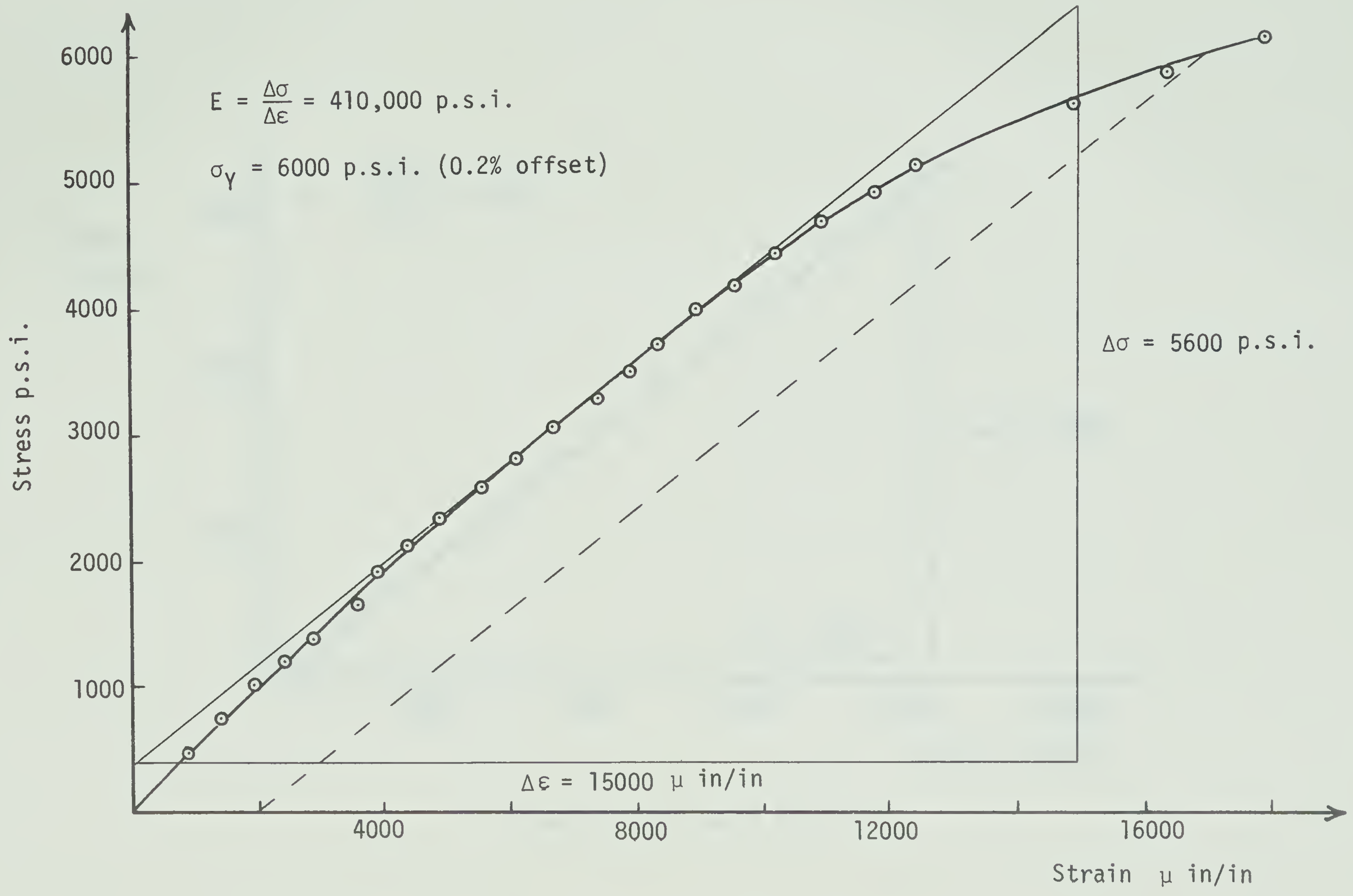

Figure A4 Tensile Test

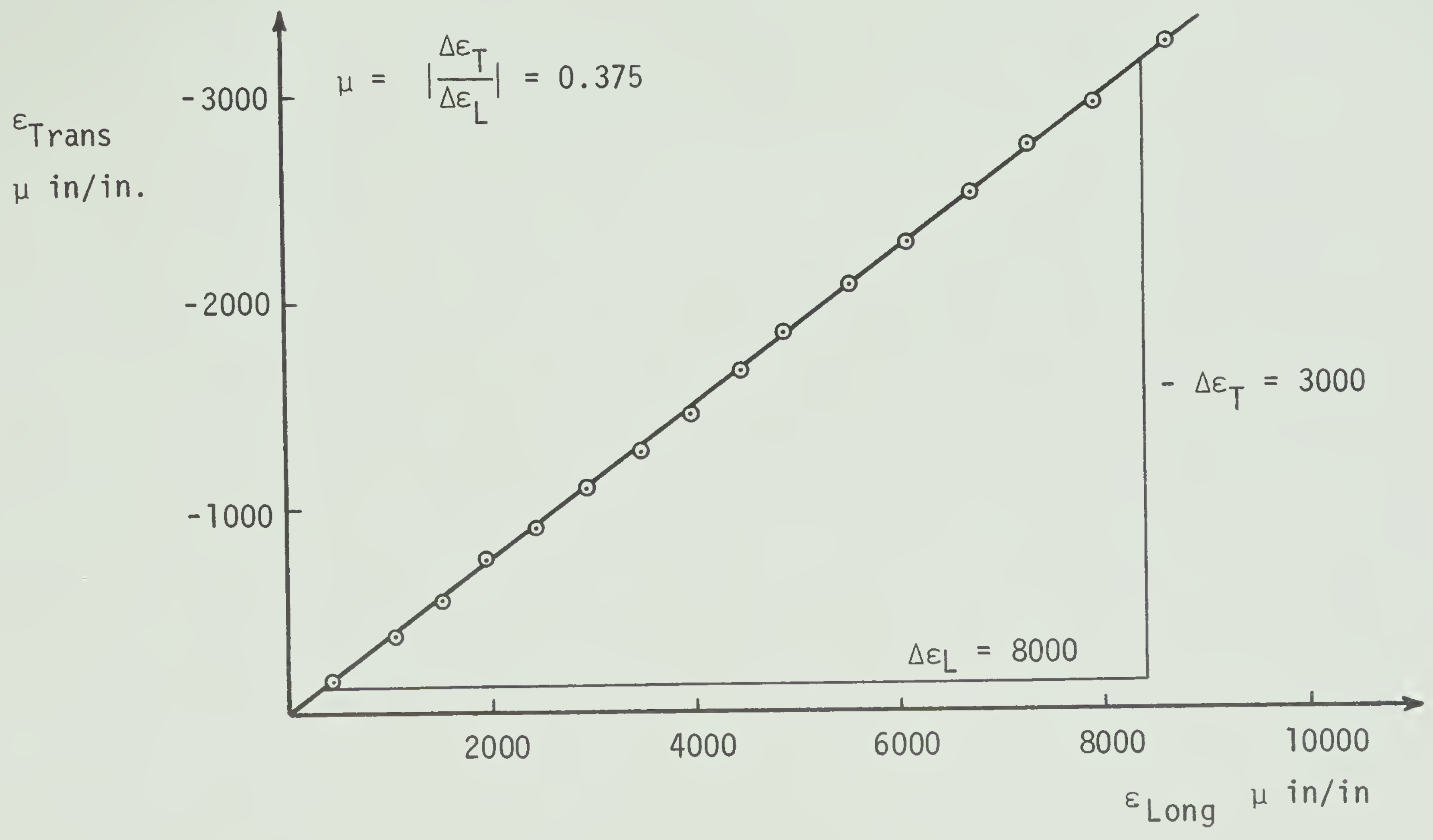

Figure A5 Poissons Ratio